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Recommended Regeneration Strategies for Active Diesel Particulate Filters with Electrically Induced Filtering Media to Enhance Filtration Efficiency

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ABSTRACT

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The people of the world have become conscious of the effects human beings are having on the earth. This awareness has spawned a willingness to regulate the amount of pollution from fossil fuel combustion that human beings place on the environment. In the United States, the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) determine and regulate the emissions standards of on-and-off road engines through emissions testing. As emissions standards become more stringent, the demand to retain the efficiency of these engines is necessitated by pending fuel economy standards and customer acceptance. Diesel engines are implemented in various applications and range from passenger cars to heavy duty transportation of goods in the form of tractor trailers and trains, as well as most off road heavy duty equipment used for construction and farming due to their relative high thermal efficiency. However, diesel engines also produce significant particulate matter (PM).

One form of technology that can help diesel engines meet the new stringent emissions regulations is the diesel particulate filter (DPF). A DPF is used to reduce engine-out diesel PM on the order of 90%, by mass, by trapping the organic and inorganic PM and then oxidizing the organic matter at a later time. The technology has been implemented in various applications and has been a proven method of controlling PM for on-road passenger and heavy-duty diesel-fueled vehicles. However, the exhaust stream of a diesel engine is a volatile environment with pressure and temperature gradients that make the implementation and operation of DPFs a challenge. Additionally, it is necessary to eliminate the accumulated PM that deposits in the filter media.

Many different methods of oxidizing the organic fraction of PM trapped within the DPFs filter media, also referred to as regenerating, have been developed.

The focus of this study was electrically-induced burn of PM captured on sintered metal fiber media. The findings of this study concluded that there are specific parameters that should be considered when constructing a control strategy for an electrically induced regeneration scheme. These parameters include the operational backpressure limitations of the engine as well as the PM production from the engine. A diesel oxidation catalyst (DOC) showed benefits for reducing the hydrocarbons in the emissions stream as well as contributing to the PM reduction efficiency by up to 30%. It is recommended that the DPF should maintain an operational back pressure below 120 in H_2O. This maintained a soot concentration which increased the filtration efficiency above 90%. Actuating the dual chambers on a higher frequency and limiting the length of burn to retain the soot buildup and backpressure resulted in filtration efficiencies levels above 90%.

Nomenclature:

CARB – California Air Resources Board

CFR – Code of Federal Regulations

CI - Compression ignited

CVS – Constant Volume Sampling

DOC – Diesel Oxidation Catalyst

DPF – Diesel Particulate Filter

DTC – Digital Throttle Controller

EGR – Exhaust Gas Recirculation

EPA – Environmental Protection Agency

HC – Hydrocarbon

HFID- Heated Flame Ionization Detector

LETRU – Low Emissions trailer Transportation Refrigeration Unit

NDIR – Non-dispersive Infrared

PA – Power Absorber

PM – Particulate Matter

SI – Spark Ignited

SOF – Soluble Organic Fraction

SSV – Subsonic Venturi

TEOM – Tapered Element Oscillating Microbalance

THC – Total Hydrocarbons

TPM – Total Particulate Matter

TR – Thermal Regenerator

TRU – Trailer Transportation Refrigeration Unit (also Transport Refrigeration Unit)

ULETRU – Ultra Low Emissions Trailer Transportation Refrigeration Unit

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Chapter 1 Introduction

Plumes of black soot have always been indicative of diesel engines in the past. Cleaning up the emissions of compression ignition (CI) engines involves solving the problem of particulate matter (PM) production, which can be done with after-treatment technologies. On-road emissions regulations require reduction in PM in CI vehicles which is discussed in Section 2.1. With current engine control technology these regulations can only be met with the implementation of some form of exhaust after-treatment.

Diesel particulate filters (DPFs) are a viable PM after treatment technology that are capable of meeting the current regulations and standards set forth by the Environmental Protection Agency (EPA) and California Air Resources Board (CARB) [1]. DPFs are adaptable to various engine applications once the control strategies are developed. This adaptability is due to the action of regeneration that occurs within a DPF when the trapped PM is oxidized into CO_2 and water with the by-product of ash. The versatility of these devices extends even further by enhancing their operation with control and operation strategies as well as advanced filter media materials that supplement the efficiency of regenerations. There are two main types of DPFs, passive and active. Passive DPFs are PM traps that have no external means of regeneration and are completely reliant upon the thermal capacity and flow rates of the exhaust stream. Actively regenerated DPFs can employ various methods of regeneration and include ignition of PM with supplemental pilot injection upstream or on the filter media, microwave ignition, and electrically induced oxidation. The method of active regeneration that is important in regards to this research is a method of electrically inducing controlled oxidation of captured PM.

1.1 Background

It is important for engine manufacturers to maximize the viability of diesel engines because they are at the foundation of trucking and freight industries and offer better fuel economy to consumers of vehicles and equipment powered by these engines compared to other alternatives such as spark ignition (SI) engines. Unlike conventional SI engines, diesel engines operate with greater thermal efficiency. It is however the means in which a diesel engine operates that both gives it an advantage in regards to its efficiency, and challenges to overcome in the form of engine out emissions. Diesel engines operate in a lean manner and power production is related to the amount of fuel injected, this behavior produces PM.

The technology that was investigated in this research utilized an active regeneration strategy to meet EPA and CARB compliance for PM. To meet this compliance, PM filtration of the exhaust is one of the options used to reduce tailpipe out PM. This is very challenging because the operation of a diesel engine results in a wide span of parameters that must be considered. One of the most important parameters is exhaust back pressure [2]. Filtration of the exhaust system increases back pressure because of blockage of the exhaust stream with some type of porous media. This parameter is important because a diesel engine can be considered as an air pump, and when it is more difficult to move air through the system the efficiency decreases in the form of increased fuel consumption or decreased engine power. This parameter is counterproductive to the design of the DPF because to maximize filtration efficiency the filter has to have a relatively low porosity. This low porosity results in an increased back pressure, so a balance between filtration efficiency and back pressure must be met. The loading of soot on the filter also plays a large role in the filter operation; this is because as the filter loads with soot the filtration efficiency increases due to soot clogging the filter media. To facilitate the control of engine back pressure a pressure transducer is used to monitor the back pressure and used in an active regeneration strategy to maintain acceptable back pressure and trapping efficiency. It is also important that the filter not regenerate entirely so as to maintain the higher filtration efficiency.

1.2 Long Term Goal, Central Hypothesis and Significance

The long-term goal of this study is to reduce the PM emissions of a V2203 Kubota diesel engine so that it meets the CARB criteria for allowable measurements of 50% PM reduction in low emission trailer refrigeration units (LETRU) and 85% PM reduction in ultra low emission trailer refrigeration units (ULETRU) in class 8 tractor trailers equipped with refrigeration units [3]. This engine is used primarily in on road tractor transportation trailer refrigeration units (TRU). TRU engines are regulated under the off-road engine emissions regulations and must conform to tier level emission standards. Although the CARB retrofit regulations do not yet exist for this application on -road nationally, they are on the horizon and technology must exist to meet the future needs of the transportation industry. To do this a series of 8-mode tests were performed on the engine with and without DPF after treatment devices. The PM from DPF devices and from engine-out conditions was evaluated gravimetrically so as to calculate DPF filtration efficiency. The goal of the study was to analyze the regenerations as well as identify variability associated with the PM captured. Another goal was to identify parameters that affect regeneration efficiency and postulate methods to control them.

The central hypothesis is that within the operation of the DPF there are trends in the data that could be used to enhance the DPF efficiency and operation. The composition of the PM was analyzed gravimetrically and for the content of soluble organic fractions (SOF).

The specific DPF investigated in this research functioned by forcing the exhaust stream through one of two chambers that contain the DPF media. The filter media was constructed of a sintered metal fiber. This type of media was utilized because the method of regeneration facilitates oxidation of the media by inducing an electric charge. Other types of filter media are made from substances like cordierite and do not provide a method to induce an electrical charge. The DPF was loaded with PM by allowing one chamber to be open to exhaust flow, while the secondary chamber was closed. The loading level of each chamber was controlled by a pressure sensor that triggered actuation, or changing of the primary chamber to the secondary chamber. Once the primary chamber was sufficiently loaded with PM, a valve actuated and allowed the exhaust to travel into the secondary unloaded chamber. Upon the switch from the primary chamber to the secondary chamber the primary chamber which was closed off from exhaust flow and had been loaded with PM was regenerated by passing current through the filter media. Once the regeneration was completed in the closed chamber, the closed chamber was not reopened to exhaust flow until the secondary chamber was loaded with PM and ready for regeneration. This pattern of operation was reproduced throughout the operation of the device. An exploded view of the chamber design is shown below in Figure 1.

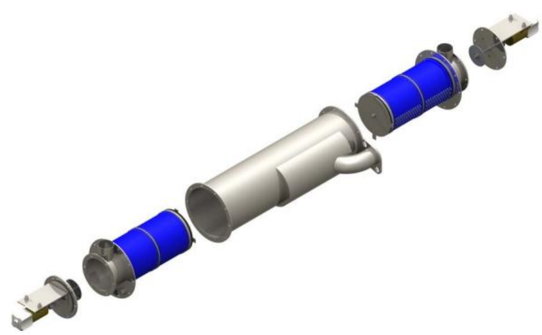

Figure 1: Schematic of TRU Particulate Matter Filter [4]

The analysis of SOFs gives insight into the engine's production of heavier particles that can affect the resulting filtration efficiencies as determined by a gravimetric analysis [5]. This type of analysis can be very useful to understanding the PM composition associated with each mode and the effect oil consumption of the engine might have on the gravimetric results. Other parameters that were considered include back pressure, exhaust temperatures, and the internal chamber actuation of the DPF. Together these encompass the primary parameters that were of importance in this study.

Below is a list of studies that were performed to meet the above criteria.

1. Determining the filtration efficiency of the DPF gravimetrically by running a series of 8-mode tests along with a baseline.
2. Determining the effect that a diesel oxidation catalyst (DOC) had on the operation of the DPF, by implementing the device pre-DPF and assessing the PM and emissions effects.
3. Passive operation of the DPF to determine trends with the self-regeneration and efficiency associated with the DPF without regeneration.
4. Analysis of the gravimetric filters used to determine the filtration efficiency for SOFs through a toluene extraction method.

The initial control strategy that was implemented in the devices analyzed in this study did not reliably achieve a filtration efficiency that met the CARB standards for on-road diesel emissions for 2011. The focus of this investigation was to assess the control strategies of this type of DPF and make recommendations to enhance its efficiency. This was done by utilizing a dynamometer to perform steady state investigations of the engine with a DPF equipped on the exhaust. The exhaust emissions were then diluted in a dilution tunnel where samples were transferred to gaseous emissions equipment as well as a PM sampling system. The emissions analyzers produced a continuous stream of data for all gaseous constituents of exhaust and the collected PM allowed for gravimetric analysis of the total PM produced at each steady state operational set point. This setup is discussed in greater detail in Chapter 3 Experimental Setup.

1.3 Objectives

The objectives for this research were:

1. Determine regeneration behaviors of the specific DPF technology under study.
2. Examine the variability associated with the PM captured on the gravimetric filters.
3. Determine the effect that SOF production of the engine had on the gravimetric PM results.
4. Identify parameters that affect the regeneration efficiency of the system and postulate methods to control them.

Chapter 2 Literature Review

2.1 Emissions Regulations

Emissions regulations in the United States have existed since the 1970s for light and heavy duty vehicles and have targeted NOx and PM reductions for heavy duty engines since the late 1980s. Heavy duty regulations have become stricter over the last 20 years. These standards were constantly raising the bar for manufacturers by pushing towards cleaner engine operation and regulations for engine efficiency are right around the corner. The industry responded by utilizing new technologies and advanced control systems to meet these regulations. This study focused on diesel engine technology which is predominantly found in heavy duty vehicles. Although diesel engines are utilized in light and medium duty vehicles in the United States their prominence lies in the heavy duty regime because of the reliability and power outputs associated with them. The emissions standards for these applications are different than that of light and medium duty vehicles. Table 1 below shows emissions standards for heavy duty diesel powered vehicles. The chart starts in the mid-1970s and shows the increase in regulation into the first decade of 2000. The chart also shows that in the early 1970s there were very few regulations and that PM was first regulated in 1988. Since 1989 the allowable amount of PM and NOx produced has been decreased by about two orders of magnitude. Relatively high NOx and PM levels were indicative of heavy duty diesel engine operation before regulations. Since diesel engines operate in a lean manner, there is excess oxygen in the combustion process. It is this behavior of diesel engines that causes them to produce NOx in a greater abundance than that of a SI engine. NOx is formed at high temperatures where there is an abundance of nitrogen and oxygen. The combustion process of a diesel engine creates an ideal environment for the production of NOx; this is because diesel engines have an abundance of oxygen in the combustion chamber upon ignition. The combustion process leaves excess nitrogen and oxygen together at high temperatures. Subsequently NOx is formed within the combustion chamber. Regulation of emissions is important not only for environmental affects, but also the harmful affect they have on human beings.

Table 1: Heavy duty diesel emissions standards [6]

<table>
<tr><th></th><th>Year</th><th>HC (g/bhp-hr)</th><th>NMH C (g/bhp-hr)</th><th>NMHC + NOx (g/bhp-hr)</th><th>NOx (g/bhp-hr)</th><th>PM (g/bhp-hr)</th><th>CO (g/bhp-hr)</th><th>Idle CO (percent exhaust gas flow)</th><th>Smoke[a] (Percentage)</th><th>Useful Life (hours/years/miles)</th><th>Warranty Period (years/miles)</th></tr>
<tr><td rowspan="10">Federal[b]</td><td>1974-78</td><td>-</td><td>-</td><td>16</td><td>-</td><td>-</td><td>40</td><td>-</td><td>20 / 15 / 50</td><td>-</td><td>-</td></tr>
<tr><td>1979-84</td><td>1.5</td><td>-</td><td>10</td><td>-</td><td>-</td><td>25</td><td>-</td><td>20 / 15 / 50</td><td>-</td><td>-</td></tr>
<tr><td>1985-87</td><td>1.3</td><td>-</td><td>-</td><td>10.7</td><td>-</td><td>15.5</td><td>-</td><td>20 / 15 / 50</td><td>LHDDE: - / 8 / 110,000
MHDDE: - / 8 / 185,000
HHDDE: - / 8 / 290,000</td><td>-</td></tr>
<tr><td>1988-89</td><td>1.3[d]</td><td>-</td><td>-</td><td>10.7</td><td>0.6</td><td>15.5</td><td>0.5[c]</td><td>20 / 15 / 50</td><td rowspan="5">1990-97 and 1998+ for HC, CO, and PM:
LHDDE: - / 8 / 110,000
MHDDE: - / 8 / 185,000
HHDDE: - / 8 / 290,000
1994+ urban buses for PM only:
- / 10 / 290,000
1998+ for NOx:
LHDDE: - / 10 / 110,000
MHDDE: - / 10 / 185,000
HHDDE: - / 10 / 290,000</td><td rowspan="5">5 / 100,000 [q]</td></tr>
<tr><td>1990</td><td>1.3[d]</td><td>-</td><td>-</td><td>6.0</td><td>0.6</td><td>15.5</td><td>0.5[c]</td><td>20 / 15 / 50</td></tr>
<tr><td>1991-93</td><td>1.3</td><td>-</td><td>-</td><td>5.0 [ABT]</td><td>0.25 [ABT] 0.10[e]</td><td>15.5</td><td>0.5[c]</td><td>20 / 15 / 50</td></tr>
<tr><td>1994-97</td><td>1.3</td><td>-</td><td>-</td><td>5.0 [ABT]</td><td>0.1 [ABT] 0.07[f], 0.05[g]</td><td>15.5</td><td>0.5[c]</td><td>20 / 15 / 50</td></tr>
<tr><td>1998-2003</td><td>1.3</td><td>-</td><td>-</td><td>4.0 [ABT]</td><td>0.1 [ABT] 0.05[g]</td><td>15.5</td><td>0.5[c]</td><td>20 / 15 / 50</td></tr>
<tr><td>2004-2006[h]</td><td>-</td><td>-</td><td>2.4 (or 2.5 with a limit of 0.5 on NMHC)[o] [ABT[i,j]]</td><td>-</td><td>0.1 0.05[g]</td><td>15.5</td><td>0.5</td><td>20 / 15 / 50</td><td rowspan="2">For all pollutants: [p]
LHDDE: - / 10 / 110,000
MHDDE: - / 10 / 185,000
HHDDE: 22,000 / 10 / 435,000</td><td rowspan="2">LHDDE: 5 / 50,000
All other HDDE: 5 / 100,000 [q]</td></tr>
<tr><td>2007+[h,k,l,m,n]</td><td>-</td><td>0.14[o]</td><td>2.4 (or 2.5 with a limit of 0.5 on NMHC) [ABT]</td><td>0.2[o]</td><td>0.01</td><td>15.5</td><td>0.5</td><td>20 / 15 / 50</td></tr>
</table>

CARB, acting as a test bed, is typically the first regulatory authority to implement new emissions standards which are then adopted by the EPA and implemented nationally. California, under the direction of CARB, was the first state to implement emissions testing into a standard yearly automotive inspection. Specifically, this research was concerned with the regulations set forth for the TRU by CARB. Two stages of regulations were implemented and Table 2 below shows the percentage PM reduction expected to be achieved in regards to the power of the engine on which the device is implemented. Nitrogen dioxide (NO_2) is also regulated for the TRU retrofit program; this is because DPFs which are not regenerated by a method that is controlled by engine operation typically utilize catalytic coatings that react with greater efficiency in the presence of NO_2. Hence for typical DPF operation NO_2 generation greatly affects the efficiency of operation of such a device. The limits for NO_2 effective as of 2009 as stated by CARB describe a 20% reduction by mass from the baseline emission [7]. In regards to the device investigated in this study, NO_2 plays no role in the regeneration process because it is not reliant on a catalytic coating whose efficiency of PM reduction is dependent on NO_2. Subsequently the production of NO_2 for this investigation remained nearly constant.

Table 2: TRU emissions standards CARB certification [3]

Low-Emission TRU In-Use Perfromance Standards		
Horsepower	Engine Certification	Retrofit with Verified Diesel Emission Control Stragety
Less than 25	0.3 gram per hp-hr	Level 2 or better (at least 50% PM reduction)
25 or Greater	0.22 gram per hp-hr	Level 2 or better (at least 50% PM reduction)
Ultra-Low Emission TRU In-Use Perfromance Standards		
Less than 25	NA - must retrofit or replace	Level 3 (at least 85% PM reduction)
25 or Greater	0.02 gram per hp-hr	Level 3 (at least 85% PM reduction)

The rate at which this technology is to be implemented is shown in Table 3. Older production engines are given a longer period of time to become compliant than that of the newer engines in an attempt to phase in the new standards. An amendment to these regulations in 2008 shifted the compliance date by a full year because the technology did not yet exist to meet the regulations.

Table 3: Implementation chart for TRU compliance [3]

In-Use Performance Standard Compliance Schedule for TRUs and TRU Generator Sets

Engine Model Year	Compliance Date for LETRU Standard	Compliance Date for ULETRU Standard
2001 or older	December 31, 2008 (See Note 1)	December 31, 2015
2002	December 31, 2009	December 31, 2016
2003	December 31, 2010	December 31, 2017
2004 (<25 hp)	December 31, 2011	December 31, 2018
2004 (≥25 hp)	Skip to ULETRU	December 31, 2011
2005 and Subsequent	Skip to ULETRU	December 31st of the model year + 7 years

Note 1: The compliance date for model year 2001 and older engines to meet the low-emission standard was delayed until December 31, 2009.

2.2 Health Effects

The health effects of PM on human beings can be substantial if there are high particle concentrations. Diesel engines produce PM in the form of visible soot particles that exit from their exhaust stacks as well as unseen particles that escape detection of the human eye. With the implementation of exhaust after-treatment, such as the device investigated in this study, there is a size distribution associated with the engine out PM. The particles produced range from what is considered to be "large," referring to visible particles, to ultra fine which are at an order of magnitude less than 0.05 to 0.1 μm [8]. The nose and lungs of a human act as a filter and the larger particles greater than 5μm can become trapped in them. Particles that are smaller than the barrier of the lungs, less than 5μm, can penetrate the body's natural defense [8]. These fine particles can pass straight through the body's natural filtration system and end up directly in the blood stream [8].

A study was performed by the National Institute of Environmental Medicine to investigate the effects that diesel exhaust have on human beings [8]. Diesel engines account for a majority of particles in urban areas that are densely populated. Slight exposure to diesel exhaust can cause a variety of issues and include irritation of eyes and nose as well as changes in the respiratory functions of the lungs. More drastic affects can be observed in the form of headaches and nausea. If prolonged exposure to elevated concentrations of exhaust occurs, the detrimental health effects increase as well as their level of detriment. It is also theorized that diesel exhaust has affected the allergic responses within populations. The theory states that irritation by the exhaust causes an increased sensitivity due to the initial irritation or that allergens latch onto the particles and are transported deeper into the lungs where they are more harmful. While diesel exhaust is comprised of various particle sizes ranging from visible particles to ultra fine particles, the smallest particles that penetrate the lungs and enter the blood stream may cause an increased susceptibility to the development of cancers as well as the cardiovascular and immune system problems [8].

2.3 Passive and Active DPF Systems

Passive DPFs are PM capturing devices that do not have an active means of regeneration. This type of DPF is reliant upon either external regeneration or increased engine thermal output. A passive DPF may be removed from a vehicle and regenerated once the back pressure becomes too great for reliable engine operation. This method has been utilized on city transit buses that have defined drive cycles and maintenance schedules. Still yet a passive DPF may be regenerated by increased thermal output of the engine or may occur during the typical operation of the vehicle. This is done by increasing the heat content of the exhaust along with the flow rate by running the engine at an increased speed for a prolonged period of time, which allows the passive DPF to regenerate. In the United States passive DPFs are typically constructed of a cordierite material that has some type of catalytic coating, this is based on the available technology currently on the market. The catalytic coating allows for oxidation of soot at lower temperatures. Passive DPFs are typically employed on diesel engines that have a fixed operation, such as a fixed engine speed in a diesel generator that is reliable enough to guarantee safe operational back pressure over the loading period. Some highway vehicles that operate at thermal capacities great enough for reliable regeneration also implement passive DPFs

Active DPFs are typically used when the operation of an engine is dynamic and requires regeneration when engine output does not have the thermal capacity for passive regeneration. There are many different types of active regeneration methods. The most prevalent is supplemental injection of fuel that is ignited to increase the exhaust temperature so as to oxidize the PM captured within the filter media. Catalytic coatings are also commonly used to lower the temperature required by the active control strategy. Sintered metal fiber filter media that is regenerated by inducing an electric current is the method utilized by the device in this study.

Additional forms of regeneration have also been developed such as microwaves that are used to raise the temperature of PM until it is oxidized. Regardless of the regeneration method each requires additional energy for operation whether it comes from power from the vehicle's electrical system to heat a substrate or directly from fuel injected into the exhaust stream.

2.4 Regeneration Strategies and Investigations

2.4.1 Thermal Response of Active Regeneration

Regeneration strategies for diesel particulate filters are important for the integration of this technology into real-world applications. One of the hurdles for this technology is that the exhaust stream has a relatively low temperature in regard to a temperature that would be sufficient for DPF regeneration. Other key factors that Rumminger and his associates take into consideration are the thermal response during soot regeneration as well as the soot oxidation rate [2]. Since many DPFs employ the use of catalyst coatings on the filter media to enhance the operation of the DPF, both catalyzed and bare substrates were investigated. Typically a DPF will regenerate within a temperature range of 500˚C to 600˚C and the addition of the catalyst can lower the regeneration temperature by up to 300˚C.

Most on-road diesel engines operate under transient conditions due to changing traffic or terrain conditions that the driver must account for during operation. It is this transient behavior that causes many issues for the DPF. Inconsistent regeneration and partial regenerations can cause burn through the substrate and damage the DPF [2]. This is a major problem when considering that the lifecycle of the engine and exhaust after treatment system must be verified or certified to over its life. A DPF must be made to be durable and work efficiently throughout this life cycle.

The composition of the exhaust stream also changes through transient activity, and this composition has a very important role in the regeneration of DPF. Other species such as oxides of nitrogen (NOx), oxides of sulfur (SOx), and water (H_2O) in the exhaust stream will drastically reduce the ignition temperature of the PM. The packing of the PM is also important in the filtering process. PM initially building up on a new or “green” filter will actually enhance the filter’s efficiency. PM can gather in two general ways and include loose contact and tight contact. Tight contact forms when the PM is packed densely and loose contact occurs when very few contacts occur between the PM and catalyst [2].

The experiment described in the study by Rumminger et al. [2] utilized a hot-gas flow reactor (HGFR); this allowed regeneration experiments to be simplified, because the PM production was fixed. The setup in this study allowed a DPF to be loaded with 4 to 8 g/L where g represents grams of diesel PM and L represent liters of volume contained by the DPF. The DPFs were weighed before and after the test. Regeneration was characterized by a pressure drop across the DPF. The weights were taken once the DPF was allowed to cool to room temperature [2].

The results of Rumminger et al. showed that a catalyst coating on the DPF reduced the pressure drop over the DPF once the PM initially began to oxidize. The activation energy of the PM of a non-catalyzed filter was 85 kJ/mol of PM and the activation energy of catalyzed filter was 38 kJ/mol. It was found that attempts to dampen DPF inlet temperature variations through increasing the heat capacity resulted in diminishing PM reduction returns at high values of heat capacity. It was also discovered that a time varying temperature input to soot loaded DPF can cause a faster regeneration, but catalytic coatings and substrate formation have a much greater influence on filtration efficiency [2].

2.4.2 Regeneration's Effect on Fuel Economy

Singh and associates investigated the drawbacks of the application of DPFs to fuel economy [9]. As a DPF became loaded with soot an increase of back pressure for the engine was observed. This increase in back pressure caused an increase in pumping losses through the engine. Any increase in back pressure adversely caused an increase in the fuel consumption, because as the engine attempts to vent exhaust out of the valve more energy is necessary to move it. This results in a loss of momentum of the air entering the cylinder which correlated to a loss of power per unit of fuel injected. To achieve a regeneration of the DPF, either the exhaust or the filter media temperature must be raised. Whether this is achieved by pre-injection of fuel or an electrical device, the energy required for this temperature rise increased the parasitic loss from increased size of the alternator or resulted in an increase in fuel consumption.

The configuration investigated by Singh and associates returned results that showed that the most economical way to achieve regeneration is through higher DPF inlet temperatures. This higher temperature would be variable for each engine to which that this is applied. The idea is to create a faster burn of the soot. This faster burn actually returns a sharper reduction in back pressure. Hence only spikes of increased fuel consumption would occur as opposed to a slow regeneration that would have a larger back pressure that would gradually diminish, which would result in a longer instance of elevated back pressure [9].

It was shown that the actual increase in fuel consumption is negligible in contrast to a pre-burner method of injecting fuel to induce fuel generated regeneration. This means that a method of injecting fuel is a difficult technology to consider when the EPA plans on increasing fuel economy regulations substantially [9].

2.4.3 Two-Stroke Diesel Analysis to Quantify the Effect of Oil Consumption

The regeneration strategies investigated by Czerwinski et al. involved throttle induced regeneration, additives, and the use of a catalytic converter pre DPF [5]. The 2-stroke engine from a bus provided the necessary PM to examine the effects of heavier particles on DPF regeneration. In a 4-stroke engine a DPF will receive exhaust contamination from oil droplets; this study is of importance because 2-stroke engines have larger amounts of oil contamination in the exhaust stream.

Another challenge behind the 2-stroke engine is that it has a lower exhaust gas temperature. A 2-stroke engine has a greater sensitivity to back pressure so regeneration strategies are particularly challenging. The PM emission rate is on scale with that of a 4-stroke engine, but due to the increase in the consumption of the lubricant the SOF levels are nearly twice as much. To counteract these challenges the addition of a pre-DPF catalyst was implemented to help achieve ignition of the soot. This is done by pre-DPF removal of the oil droplets resulting in a PM delivery of a relatively dry nature. A Lubrizol DPF was then tested and the catalytic coating on this DPF actually did not allow the DPF to achieve a loaded state, because it was constantly regenerating. This DPF however did increase the production of NO_2 on the order of 20-40% [5].

The general results of the engine test setup determined that a large portion of the particle mass was emitted through oil droplets. It was also determined that the implementation of a wire mesh filter catalyst would oxidize these droplets and curtail the SOF and PM [5].

Many parameters were defined that affect how a DPF can be sized to its particular application. The major parameters being: exhaust outlet temperature, the exhaust composition, thermal mass of the DPF, and the time varying rate of soot loading that the operation produces. This study shows that sizing a DPF and adapting it to standard operation is a dynamic process and requires a balancing of many different parameters [5].

2.4.4 Actively Regenerated DPFs and Incomplete Regeneration

Incomplete regenerations and partial loading can result in failure of the DPF, so distribution of soot and strategies to evenly burn off the collected soot are very important to the life cycle of a filter. Partial regenerations leave an inconsistent amount of soot across the DPF and this non-homogenous distribution across the media produces an inconsistent burn that promotes uneven temperature gradients that distort and can even destroy the filter media [10].

The test method employed by Pinturad et al. consisted of DPFs that were loaded with PM at a flow rate of 7 g/L [10]. The soot loading rate was then analyzed and produced a non-linear trend. This trend is explained with the deposition of soot. The soot collects in a homogenous layer across the cake, but does not hinder the flow of exhaust, so the filtration efficiency increases rapidly until the loading achieves a higher cake layer depth that does not promote flow. As the soot layer increases beyond this point the back pressure continues to increase until a regeneration event occurs. The efficiency of the regeneration is determined by comparing a ratio of the mass of the soot regenerated and mass of the soot loaded. It is important to note that this method of calculating trapping efficiency was not utilized in the study performed herein and is merely the method used by Pinturad et al. in a study that is of interest. In this test scheme both of these values were determined by controlling the amount of preloaded soot within the DPF. The oxidation of the soot starts primarily at locations within the media of the highest concentration of soot. Once these initial focal points have initialized burn they spread until a homogenous burn across the filter is achieved [10].

The findings of Pinturad and associates concluded that the soot begins to oxidize within the wall of the media [10]. It was also shown that soot deposits during regeneration events. The density of the compacted soot across the media reflects points of maximum temperature gradient. It was shown that controlling the deposition of the soot in a manner that promotes homogenous dispersion increased the longevity of a DPF and reduced the severity of internal temperature gradients within the DPF.

2.4.5 Active DPF Regeneration and the Effects of Internal Temperatures

A study performed by Kong et al. assessed the viability of an active clean thermal regenerator (TR) for application in diesel engines regulated to 2007 standards as set forth by the EPA [6]. This study delved into the internal temperatures experienced by the DPF. These internal temperatures are very important when examining a DPF's performance because many DPF device failures are driven by the thermal stresses induced by temperature gradients. Nine temperature sensors were placed within the DPF housing in a symmetric pattern with one at the center and eight sensors aligned around it evenly spaced near the edge. The testing was performed by loading the DPF with soot for varying durations. To produce a worst case scenario to achieve the maximum temperatures that would be experienced by the filter media the regeneration was started and the engine was immediately brought to idle. This drop in the exhaust flow through the DPF would cause the temperature to increase rapidly. A loading time of four hours at a soot flow rate of 4 g/L produced internal temperatures peaking at 930˚C. This temperature was below the design limits of the filter media contained in the TR unit. An increment of one hour and an increase from 4 to 5 g/L of soot produced temperatures near 1020˚C. This temperature was beyond the limits and would affect its integrity. The conclusion of this study showed that the TR system could meet the criteria set forth by the EPA for 2007 regulations [1].

2.4.6 The Effect of Catalytic Coatings on Soot Accumulation and Regeneration

A catalyzed DPF with active regeneration was investigated by Guo et al. for its viability in implementation on diesel engines with a need for PM reducing emissions equipment [11]. The principle of operation of this system was the reaction of the catalyst to a quantity of diesel fuel injected into the system. This injection of fuel produced an exothermic reaction that allowed the soot to oxidize or burn off. The DPF showed an effective 99% efficiency when reducing PM. The objective of their study was to determine a range of operation for the DPF so as to achieve efficient PM removal, as well as acceptable exhaust emissions, and fuel economy.

Darcy's law ($\frac{Q}{A} = \frac{\Delta P}{\mu R L}$) was used to calculate the pressure drop and flow rate of exhaust as it was passed through the media. This is important because the back pressure is a key component to successful engine performance while utilizing a DPF on a diesel engine. The R variable in Darcy's equation represents a restriction value. This R value changes throughout the operation of the DPF. The initial value of R is dependent solely on the media itself, however as soot is captured on the media the passageways for the exhaust become blocked and the restriction value increases. The application of Darcy's law produced a linear relationship of pressure drop and space velocity. The regeneration was directly affected by the amount of soot loaded on the DPF as is witnessed with a higher restriction value. When the DPF exhibited a higher restriction value, the result was higher DPF temperatures and shorter regenerations. This is directly correlated to the amount of available O_2. The effect of regenerating the DPF had less of an impact on fuel consumption when the exhaust was at a higher temperature and higher frequency of regenerations. It is important to balance these parameters, because increasing the exhaust temperature adversely affects the life span of the filter media [11].

2.4.7 Uncontrolled Regenerations

Regeneration of a DPF can be detrimental to the life of the DPF, when the regenerations do not occur in a controlled manner. The effects of an uncontrolled regeneration are increased internal temperatures and mechanical failure of filter media. A study by Zhan et al. outlines three different failure criteria. The first of which is defined as an uncontrolled high initial temperature once the DPF starts regeneration (Type A). The second (Type B) is defined as an uncontrolled regeneration that occurs when the DPF is in a regeneration mode, but the engine is brought down to idle causing an extreme rise in internal temperature from temperature near 550˚C to over 1100˚C, also referred to as a "runaway" regeneration. The third (Type C) failure criterion is the uneven distribution of soot on the media, which causes localized inconsistencies in temperature concentration causing thermal stresses on the filter media [12].

One of the challenges of design strategies for an actively regenerated DPF is that during the life cycle of the device it undergoes repeated loadings and regenerations. So as a DPF goes through dynamic loadings and regeneration states it experiences a variety of conditions. It is the balance of the oxidation of the PM and backpressure produced by the DPF that is the main concern for the general operation of the DPF. A DPF operates within a system being that of the exhaust stream of a diesel engine whose environment can change rapidly on a second by second basis. Without proper management of Types A, B, and C failure criteria, the application of actively regenerated DPFs would be difficult to do while maintaining appropriate EPA mandated allowances for PM and providing a level of reliability for the duration of the life cycle of the engine [12].

Zhan et al. investigated the thermal behavior of the DPF at a worst case point of the DPF loaded with soot and the regeneration started. Once regeneration started, the fueling that instigated the regeneration was stopped and the engine was brought to an idle condition. This maximized the amount of O_2 in the DPF as well as minimized the flow through the system which subsequently lowers the convective heat transfer rate. This causes an immediate increase in temperature and reproduces the "run away" type B failure criterion [12].

Looking at the DPF media as both the filtering media and area of soot oxidation, it is clear to the investigators of DPFs that the method of control cannot be the soot loading. Since the engine constantly produces PM the media must constantly capture the PM, although this can be somewhat minimized by the introduction of a dual flow path filter, but this approach still just displaces the problem further down the timeline. The parameter that can be controlled is the available O_2 for the soot oxidation. Also, if the initial temperature is generally higher than is typical of the exhaust stream, then the chemical reaction within the DPF may cause the temperature to increase over a short period of time. Another problem is the deposition of the soot uniformly over the filter media's surface. This is important because the PM that is deposited can be considered to be the reactant in the oxidation process. This study also showed that if the PM is not evenly distributed across the media there will be localized areas of heat concentration, which can lead to failure of the filtering media [12].

Actively regenerating a DPF depends on a variety of variables. This study outlines the major variables that affect regeneration, these include exhaust flow rate, exhaust temperature, air to fuel ratio, as well as the concentration of O_2 in the exhaust. The goal of this study was to assess the impact of these variables as well as keep the failure modes from occurring. A table of solutions and reasons for failure was generated to summarize the findings and is shown below in Table 4 [12].

Table 4 Failure Criteria [12]

Type	Description	Reasons	Solutions
A	Excess exotherm at the start of regeneration	1) high SOF content in PM 2) High ramp-up rate of temperature	1) Closed-coupled DOC to reduce SOF content in DPF 2) Temperature ramp-up ratecontrol
B	Temperature spike caused by dramatic exhaust flow reduction during regeneration	The Combination of 1) Excess PM loading 2) High Exhaust oxygen concentration	1) Increase EGR rate 2) Intake fresh air reduction
C	Uneven temperature distribution during the regeneration process - "hot spot"	1) Incomplete regeneration 2) Uneven flow and temperature distribution	1) Flow pattern improvement "Static Diffuser" to improve flow and temperature distribution

The study performed by Zhan and his associates showed that the application of an actively regenerated DPF is possible and that control strategies can be implemented to better stream line the regenerations. The findings outline a method to eliminate uncontrolled regenerations and alleviate the complications resulting from the three types of failure criteria [12].

2.4.8 Critical Variables of the Regeneration Strategy Development and Optimization

An investigation into the operation of an actively regenerated DPF was undertaken by Suresh and his associates [13]. The method of regeneration that was implemented was the pre-injection of diesel fuel in conjunction with an inline DOC. The results of this test showed that with the configuration used in the testing it was necessary to utilize a DOC. The DOC allowed for the injected diesel fuel to be fully utilized in the uniform heating of the DPF media and prevented the passage of excess hydrocarbons downstream. Investigation into the relation of soot loading to back pressure showed that their correlation is not exact meaning that larger amounts of soot loading did not always show a direct increase in back pressure. This is due to the flow characteristics within the DPF. Although the soot is being captured within the media it does not show a linear increase in the backpressure on the exhaust system. This shows that there is not a uniform loading of the filter media with soot.

The regeneration efficiency was observed to be related to the inlet temperature of the DOC. The higher the inlet temperature the larger the regeneration efficiency recorded which was also associated with longer regeneration duration. Regenerations that occurred at 540˚C or larger were driven by the amount of O_2 that was available in the exhaust stream. Regenerations that occurred at 350˚C were attributed to the NO_2 content in the exhaust stream. This NO_2 driven regeneration is somewhat negligible for more modern engines that control the output of NO_2 by reducing in-cylinder combustion temperatures [13]. This means that the only feasible regeneration is driven by O_2 content unless NO_2 is generated by means outside the combustion chamber. The difficulty arises from the operation of a diesel engine that the duty cycle never allows the exhaust temperature to reach a high enough temperature to allow a complete regeneration of the DPF [13].

Chapter 3 Experimental Setup

3.1 Test Engine

The engine used in this study was a Kubota, four cylinder, 2.2 liter diesel engine. The specifications for the engine are provided in Table 5. The engine is used in on-road tractor trailer refrigeration units. The exhaust system of this engine was channeled through a TRU actively regenerated DPF; a DOC was used upstream of the DPF for some test configurations. The control method for operation of the DPF was driven by pressure sensors in the exhaust stream that allowed the system to determine when the filter was loaded to a pre-defined back pressure level. Note the CARB TRU regulations are intended to reduce the emissions from older engines and as such, the test engine used was at or beyond its useful life. The examination of the SOFs become important when examining these older engines that may have greater oil consumption due to wear and hence greater SOF production as compared to when the engine was new.

Table 5: Engine Specifications

Performance	Power: 30hp @ 2200rpm Torque: 95 ft-lb @1450 rpm
Engine Configuration	4 cycle, 4 cylinders In-line
Exhaust After Treatment	Active DPF with and without DOC
Aspiration	Natural Aspiration
Injection System	Indirect
Displacement	2.2 liters
Idle Speed	900 rpm
Engine Model	Kubota V2203

3.2 Exhaust After Treatment

The TRU filter was a dual chamber design which was electrically regenerated using a sintered metal fiber and is illustrated in Figure 2. The soot was accumulated on the sintered metal fiber, which was also the reaction surface for the oxidation of the soot. The sintered metal fiber was supplied with voltage which was generated by the electrical system of the vehicle. This voltage facilitated the oxidation whenever the filter's back pressure reached a predefined level. This system was also a dual chamber design with solenoid valves that controlled the individual chambers as illustrated on either side of the filter in Figure 2.

Figure 2: TRU Particulate Matter Filter [4]

When the primary chamber back pressure reached the predefined level and filter required regeneration the other chamber opened and the primary chamber closed to exhaust flow. This method allowed for control of the back pressure on the engine while still retaining the filtration efficiency necessary to reduce exhaust out PM. Figure 3 below shows the Kubota test engine with the DPF installed which is held up by a rack, and has a large dual exhaust pipe attached connected to both chamber outlets.

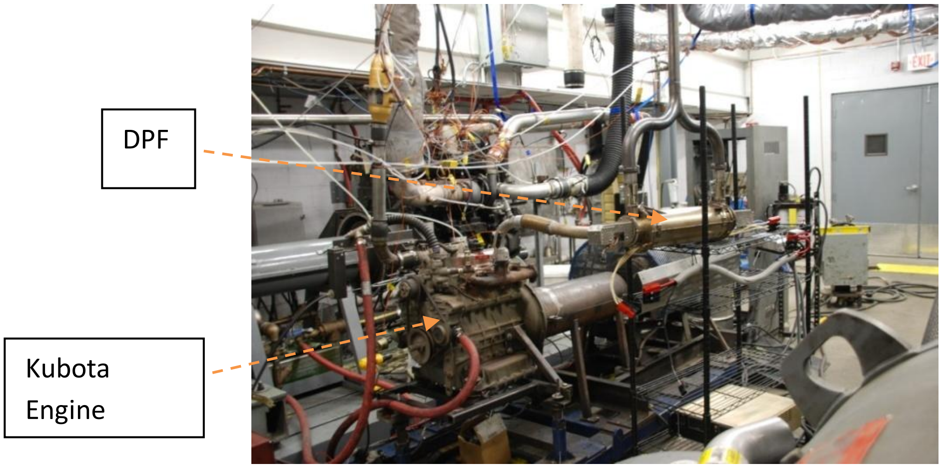

Figure 3: Filter Test Setup

3.3 Laboratory Instrumentation

The testing of this configuration took place at West Virginia University's Center for Alternative Fuels, Engines, and Emissions. A Vulkan coupler was mounted concentrically on the engine's flywheel, and a driveshaft was connected to the input shaft of a Telma CC100 eddy current power absorber (PA). A strain-gauge load cell connected between the PA's side arm and the frame measured the reactive load from the PA. The rotational speed of the engine and PA combination was recorded by a 1024 pulses per revolution speed encoder. The load and speed signals were transferred to the Mustang Dynamometer Dyn-Loc IV controller. The fueling of the engine was controlled by a Labeco servo motor connected to the Kubota fuel pump linkage, and was driven by a Mustang Dynamometer Digital Throttle Controller (DTC). Figure 4 shows the Kubota engine setup on the eddy current dynamometer with all the instrumentation for baseline testing without the DPF attached. In this configuration, the Dyn-Loc was used in "speed mode" which utilized the PA to hold the desired engine speed, while the DTC, utilizing the Labeco servo motor, adjusted the engine's fueling lever to maintain the desired torque. In operation, the main data acquisition computer sent a timed sequence of desired speed and load set points to the DTC and Dyn-Loc respectively, as well as recording the actual engine speed and side arm torque together with all the other operating parameters.

Figure 4: Dynamometer configuration

The dynamometer was located within an emissions test cell, where the exhaust was ducted to a full scale dilution tunnel and emissions sampling system that was designed to comply with the Title 40, Code of Federal Regulations Part 86 emissions regulations [13]. The dilution of the exhaust constituents occurs to replicate the interactions that the exhaust would have in a real world scenario with the atmosphere. The dilution tunnel was supplied with ambient air that had been passed through HEPA filters that remove 99% of ambient PM and was conditioned to a temperature of 25˚C ± 5˚C and a nominal dew point of 14.5˚C. The dilution tunnel operated in conjunction with a constant volume sampling tunnel (CVS). The flow of the dilution tunnel was controlled by a critical flow venturi (CFV) that allowed for the appropriate mixing of the dilution air and exhaust so that emissions measurement could take place. The emissions analyzers were supplied with samples of the diluted exhaust via heated lines from the CVS tunnel. The heated lines ensured that the sample remained at a high enough temperature to prevent the sample from condensating and affecting its integrity. The different constituents of exhaust have specific sample line temperature requirements that are outlined in the 40 CFR Part 86. The sampling systems for NOx, CO, and CO_2 were kept at 235˚F ± 20˚F. It is important to also note that the CO and CO_2 samples require the removal of water from the sample; this is done using a chiller that condensed the moisture out of the sample to keep water from reaching the analyzer. Heated, dilute sample was also delivered to a heated enclosure that housed a PM filter. The PM filter was changed for each operating point or mode of the testing. The intake air for the engine was conditioned using a HVAC unit in conjunction with a HEPA filter and the temperature was controlled so that it fell in a range from 68˚F to 86˚F. A laminar flow element was also utilized upstream of the engine intake so that the intake flow could be measured as a quality assurance procedure but was not used in the reporting of the emissions data.

Gaseous emissions measurements were generally recorded and averaged for 6 minutes after the mode achieved stability for 2 to 4 minutes. PM was recorded at the end of each mode for 2 to 6 minutes with this time dependent on mode and expected mass deposition on the filter media. The emissions of NOx, NO, THC, CO and CO_2 were all analyzed using the instrumentation listed below. A chemiluminescent analyzer was used to determine the levels of NOx and NO. The measurements were provided by an ECO-Physics analyzer. This system contained two independent analyzers, one which measured NOx and the other measured NO. The quantification of NO_2 was found by the difference between NOx and NO reading from the ECO-Physics analyzer. Measurement of THC was done with a Horiba FIA 236 analyzer incorporating a heated flame ionization detector (HFID). Three different non-dispersive infrared (NDIR) analyzers were used to measure the CO and CO_2 concentrations. High concentration levels of CO were measured using a Horiba AIA-210 analyzer and low concentration levels of CO were measured using a Horiba AIA-210 LE analyzer. A Horiba AIA-220 analyzer was used to measure CO_2 concentration.

The PM for each set point was recorded by the capture of PM on two 70mm filters (T60A20) placed in series with a sample port running from the CVS tunnel. The filter was analyzed gravimetrically in a class 1000 clean room from TAC Precision Environments, which was temperature and humidity controlled. The temperature inside the room was maintained at 71˚F ± 3˚F and the humidity at 45% ± 8%. The dew point was also controlled to be within 49˚F ± 3˚F. Gravimetric analysis was performed by a Sartorius micro balance that was on an anti-vibration table and was isolated from static discharge inside the clean room both of which are shown below in Figure 5.

Figure 5: Clean Room and Micro Balance

Gravimetric evaluation produces a total PM for each test. To assure quality gravimetric results a background filter was run through the dilution tunnel without engine operation to determine base levels of ambient PM and for any sampling artifacts. The pair of 70mm test filters was also associated with a reference pair of filters that were never used during testing to further assure data quality when comparing weight changes. As a complement to the gravimetric analysis of the PM a TEOM model 1105 was also used to monitor PM production of the engine on a continuous basis. The TEOM operates on a principle of deposition and a resulting change in a microbalance output. A tapered element captures soot and an oscillating microbalance converts this change in mass of the element into a signal that represents the PM in the exhaust.

A Soxhlet extraction was also performed to determine the level of SOF within the exhaust stream. A gravimetrically analyzed filter with captured PM was placed within a glass thimble. This thimble was then placed in an extractor that thermally cycled a mixture of 40% toluene and 60% ethanol over the filter using a boiling and condensation loop. Figure 6 shows the Soxhlet extraction setup housed within a chemical flame hood; a flame hood was necessary because the mixture of ethanol and toluene may be prone to flash boiling.

Figure 6: Soxhlet Extraction Setup

The equipment used was an Ace glassware Soxhlet extraction set. This set consisted of a condenser that was fed with cool house water at its lower port which exited via the upper port. The extractor portion housed the small glass thimble containing the PM filter and was also where the mixture condensed and cycled over the filter. A flask contained the mixture and was where the system came in contact with a heating element that allowed for boiling to occur. Figure 7 below shows the glassware setup used for this study.

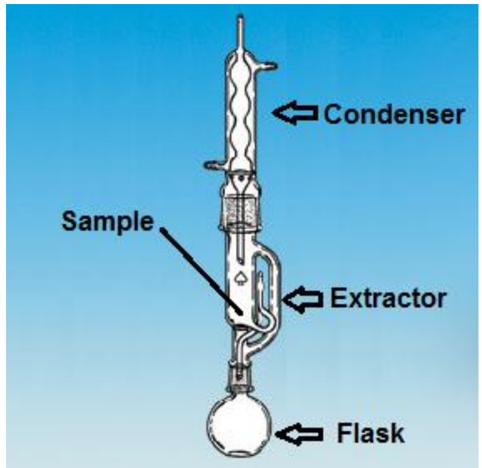

Figure 7: Soxhlet Glassware [15]

A boiling and condensation cycle time of approximately 15 minutes was used. The filter was cycled for a 12 hour period so that it could be subjected to at least 40 cycles. Cycling the toluene-ethanol blend over the filter removed the trace SOFs that were captured on it. Once the filter had been dried it was reweighed to achieve a difference of weight that was indicative of the SOF content.

Chapter 4 Approach

4.1 Determination of Engine Baseline

The test engine was configured and baseline runs were made for comparative analysis with the DPF. The engine was run through a specific 8-mode test the ISO8178-C1, while taking gaseous emissions and PM samples [16]. This was necessary to determine the filtration efficiency of the DPF, as well as any effects that the DPF may have on the gaseous exhaust emissions of the engine. The engine baselines were run multiple times to gain greater accuracy with the results of the 8-mode operation of the test engine and provide some quantification of the run-to-run variability of the engine, after-treatment , and sampling system. All further analysis of the DPF devices also utilized this 8-mode test. Table 6 shows the normalized engine operation for this test cycle along with the sample times for the gaseous and PM samples.

Table 6: ISO 8178-C1 Normalized Cycle [16]

ISO 8178-C1 Normalized Cycle								
Mode	Torque (%)	Engine Torque (ft-lb)	Speed	Engine Speed (rpm)	Weighting Factor	Mode Length (s)	Gaseous Sample Time (s)	PM Sample Time (s)
1	100	79.5	rated speed	2200	0.15	600	360	360
2	75	54.2		2200		600	360	360
3	50	36.1		2200		600	360	360
4	10	7.2		2200	0.1	600	360	360
5	100	104.9	intermediate speed	1450		600	360	360
6	75	71.5		1450		600	360	360
7	50	47.7		1450		600	360	360
8	0	0	low idle	900	0.15	600	360	360

4.2 Analysis of DPF Configurations

The engine was fitted with five differing prototypes of the TRU DPF. These devices were all supplied by a company developing DPFs for TRU application and had different characteristics with both their media and control systems. Along with the different devices, some were intended to be operated with a DOC so that some of the devices were tested with and without a DOC. Some passive analysis of the devices was also performed to investigate the occurrence of the passive regenerations that can occur in the system. Table 7 below shows an outline of all the tests and the configurations for each test.

Table 7: DPF Configuration and Testing Outline

Filter number	Description	DOC	Active	Passive	# of 8 modes	Software Change	Run ID
1	Letru	no	yes	no	3	no	E02502-01,-03
2	Letru	no	yes	no	3	no	E02503-01,-03
3	Uletru	no	yes	no	2	no	E02765-01,-02
3	Uletru	no	no	yes	1	no	E02768-01
3	Uletru	yes	yes	no	1	no	E02769-01
3	Uletru	yes	no	yes	1	no	E02776-01
3	Uletru	yes	yes	no	1	yes	E02779-01
3	Uletru	yes	yes	no	1	yes	E02779-02
3	Uletru	yes	yes	no	1	yes	E02779-03
3	Uletru	yes	yes	no	1	yes	E02779-05
3	Uletru	yes	yes	no	1	yes	E02779-06
3	Uletru	yes	yes	no	1	yes	E02779-07
3	Uletru	yes	yes	no	1	yes	E02779-08
4	Uletru	no	yes	no	1	no	E02767-01
4	Uletru	no	no	yes	1	no	E02770-02
4	Uletru	yes	yes	no	1	no	E02771-01
4	Uletru	yes	yes	no	1	yes	E02780-01
4	Uletru	yes	yes	no	1	yes	E02780-02
5	Uletru	no	yes	no	2	no	E02772-01,-03
5	Uletru	yes	yes	no	1	no	E02773-01
5	Uletru	yes	no	yes	1	no	E02775-01

The software changes for the TRU DPFs control unit affected the operational set points for the backpressure and when regeneration occurred. Due to the time constraints of this testing and the cost associated some tests did not have repeat runs. Although there is a level of uncertainty associated with a single run, based on the emissions level of the first run it could be inferred from that single run whether or not the configuration would produce desired filtration efficiencies.

4.3 Analysis of Emissions

The gaseous and PM emissions for each setup were compared to determine the trends in their production and to determine the percent difference between each device and each configuration. From this analysis of the trends of PM and emissions production the recommendations for future development of the device and its configuration were made, as well as the implementation of a DOC.

4.4 Soxhlet Extraction

To evaluate the SOF content of the PM samples additional baseline tests were required Figure 26 shows the results of the baseline tests. The gravimetric filters used for these baseline tests were also evaluated using the extraction process described above. This was necessary because the SOF analysis took place at the end of the testing, and the baseline filters from the previous testing had not been properly prepared for an extraction.

Chapter 5 Results and Discussion

5.1 Introduction

In this chapter the analysis of all the configurations of the DPF will be discussed. The results for the emissions, with an emphasis on the PM emissions, will be shown on a brake-specific mass (g/bhp-hr) basis. The PM was the primary concern in this study since this was the objective of the after-treatment devices in this study and is discussed first. The modal analysis of each constituent of regulated emissions is shown in their own section so as to compare the difference of each device in finer detail. The 8th mode is the idle set point of the engine and, by definition, produces no power so the value for PM in a brake specific sense is not tangible. The 8th mode is accounted for in the 8-mode composite analysis where all eight modes are added together in a weighted brake specific value. The filtration efficiency is shown as a percent reduction from each device's baseline runs. The TRU unit maintains the desired temperature of a trailer compartment and this lends the operation to be in a 4-mode realm of operation. Hence a TRU 4-mode composite analysis is done to better capture the effects a DPF has on the device. The final three sections of this chapter show the 8-mode weighted composite values for each device, because this is the standard for evaluating a DPF, they are also accompanied by 4-mode composite analysis which is a composite evaluation based on TRU operation, as well as the results of the Soxhlet extraction, and the final selection of the device with the best characteristics.

5.1.1 Test Parameters and Baseline Engine Tests

Each DPF configuration was subjected to an 8 mode engine test that consisted of eight engine torque settings and three engine speeds. An example measured speed and load for one test can be seen in Figure 8 below. Note that the measured engine speed had a standard deviation of 68.12, 3.16, 2.92, 2.99, 2.15, 2.19, 2.10, 1.85 rpm, respectively, for modes 1 through 8 and the measured torque had a standard deviation 6.06, 3.61, 7.21, 4.40, 1.99, 3.91, 3.22, and 0.49 Nm for modes 1 through 8, respectively.

The LETRU testing had a total of three baseline tests and the ULETRU testing had a total of three baseline tests. There are different baseline tests for each DPF type because of the time elapsed between testing. Two different engines were used in this research, but the same model was used. The LETRU testing occurred in October of 2008 and ULETRU testing took place in June of 2010. The results for both LETRU and ULETRU devices were compared to their respective baseline average. The results of these baselines were averaged for the LETRU and for the ULETRU tests and the resulting baseline data were compared to their respected baseline as well as the individual mode results. The charts below show the brake specific mass emissions for both testing campaign's baseline tests. It is important to note that CO_2 emissions are shown divided by 100 to better scale the data for presentation. As is demonstrated graphically in Figures 9 and 10 below there are some differences between these baseline values between the LETRU testing and ULETRU testing. To demonstrate these differences, values were compared and a percent difference was calculated between the baselines. Table 8 below shows the differences across the baseline values. This percent difference utilizes a calculated difference of the ULETRU subtracted from the LETRU baseline values. As illustrated in these two figures and table, there was an overall increase in the baseline emissions between the two campaigns. On average, there was a 25%, 26%, 16%, 16%, 16%, and 17% percent increase from the values recorded from the LETRU baselines for HC, CO, CO_2, NOx, NO, and PM, respectively across all modes of operation. The variability between these two campaigns could be due to the physical change of engines. Although the same model engine was used variability of engine wear could show variations of this magnitude especially coupled with fuel differences between regimes. Figure 8 also shows the difference between the set point of the dynamometer control system and the resulting engine operation. Because of the differences in the engine and fuels used, care must be exercised when comparing one device against another device.

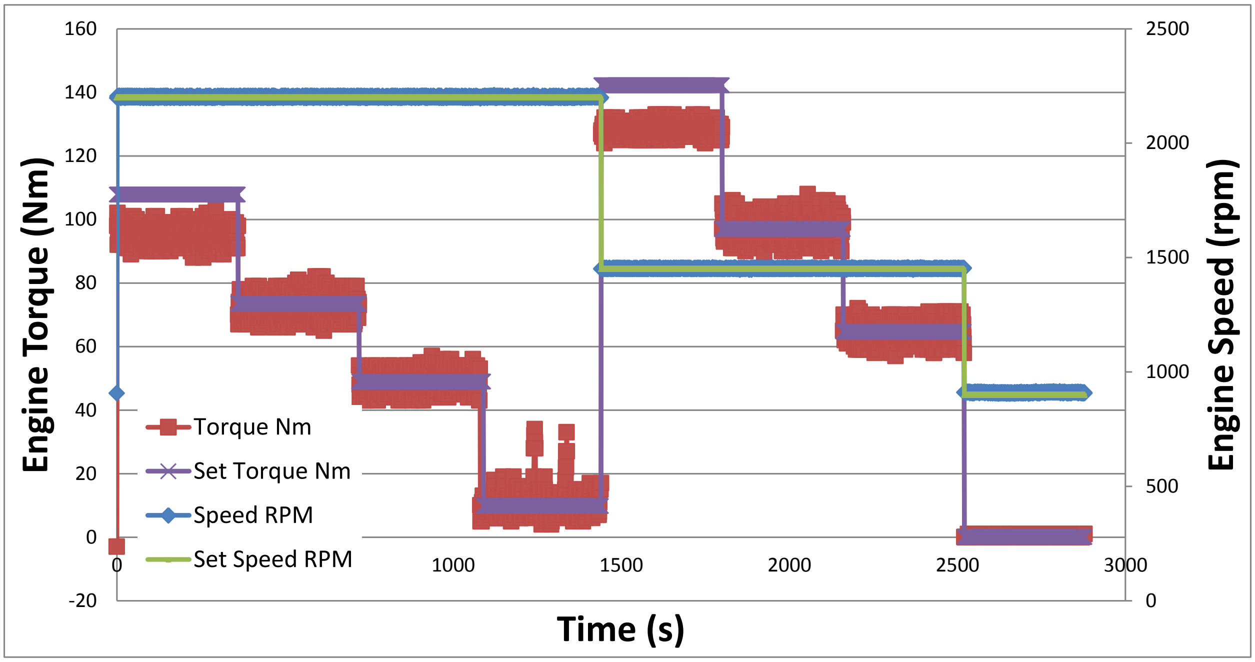

Figure 8: Measured 8-Mode Speed and Load Data

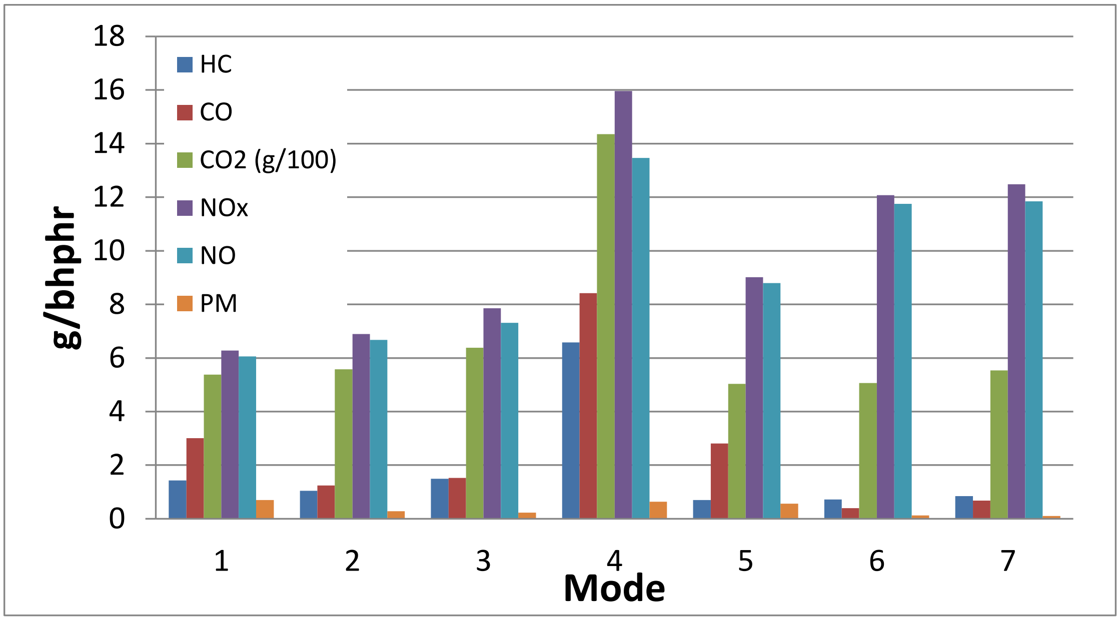

Figure 9: LETRU Brake Specific Baseline

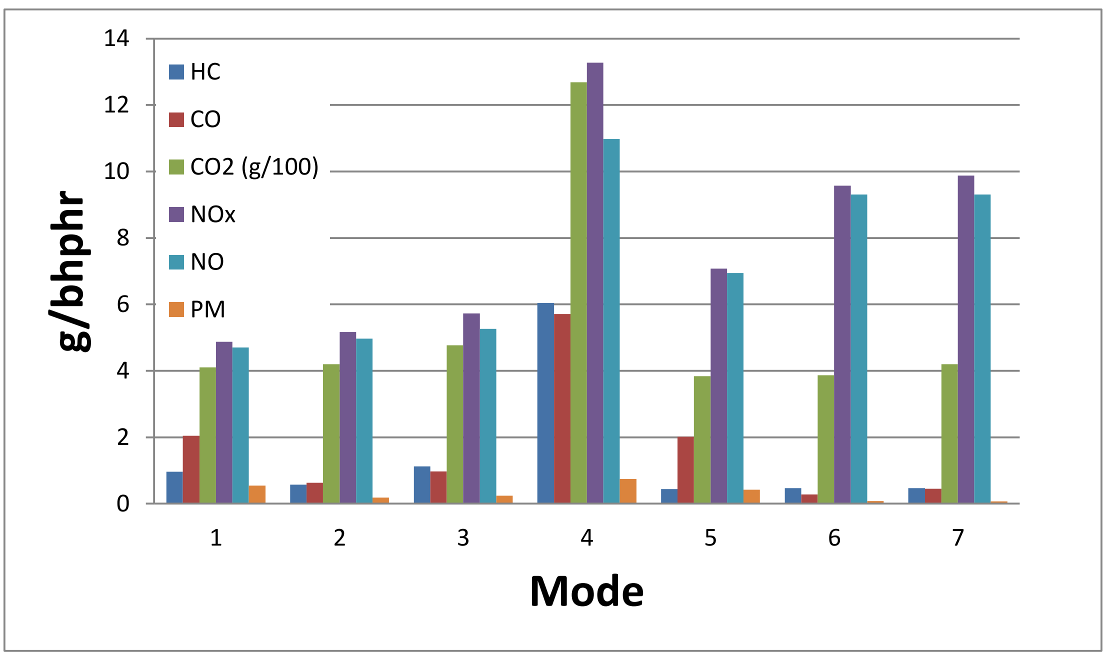

Figure 10: ULETRU Brake Specific Baseline

Table 8: Modal Percent difference for LETRU and ULETRU Baselines

Percent Difference	mode 1	mode 2	mode 3	mode 4	mode 5	mode 6	mode 7	mode 8
%HC (g/bhphr)	24.159	35.700	18.158	5.602	27.542	26.524	34.452	-
%CO (g/bhphr)	23.877	39.312	27.337	24.076	20.738	21.249	25.449	-
%CO2 (g/bhphr)	17.093	17.976	18.363	8.068	17.258	17.093	17.440	-
%NOx (g/bhphr)	16.157	18.144	19.847	11.876	15.427	14.855	14.971	-
%NO (g/bhphr)	16.071	18.644	20.608	13.104	15.085	14.903	15.407	-
%PM (g/bhphr)	16.038	27.348	2.097	9.994	19.012	21.778	21.874	-

5.1.2 Modal PM Filtration Efficiency Comparison of Devices

The filtration efficiency is a comparison of the PM captured on the gravimetric filters between the baseline and after-treatment tests. The brake-specific PM mass emissions from the after-treatment devices were compared to the brake-specific PM mass emissions from the baseline tests, allowing for the calculation of the change in filtration efficiency at each mode. A negative value represents that there was a reduction in PM for the given mode, and a positive value demonstrates that there was increased PM production for the given mode. Figure 11 below shows the filtration efficiency for all the devices investigated in this study. It is important to note that abbreviations are utilized for the characteristics of each DPF hence forth. A represents an active run, P represents a passive run, DOC shows the implementation of a DOC, and NR represents an alteration in the regeneration strategy. To further expand upon the alteration in regeneration strategy, it is important to note that actual changes were proprietary information held only by the device manufacturer. The alteration in software was indicative of changes to the duration of regenerations as well as the backpressure setting that triggered regeneration. Mode 1 is a particularly difficult mode to achieve since it the engine is operating at rated speed and 100% torque load. This mode contributes PM to the final analysis, but is rarely achieved in “real world” application of the engine. The thermal stability of this mode is also difficult to maintain because it is the first mode of the test.

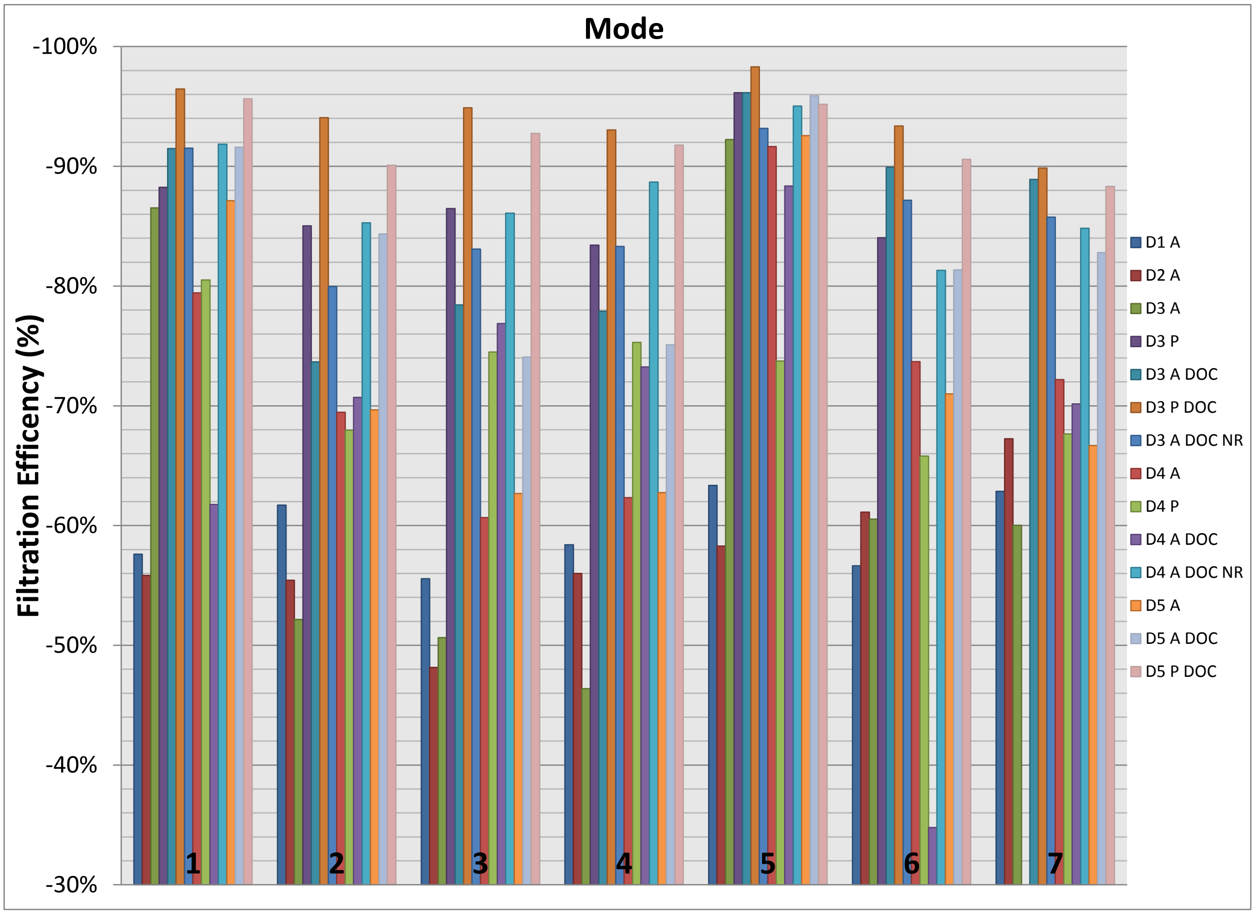

Figure 11: Brake Specific Modal PM Reduction Efficiency

As seen from the results in Figure 11, the passive runs of the devices produced the highest filtration efficiency relative to the active runs. This is because there is an increase in filtration efficiency since the PM deposited is never actively regenerated and regeneration depends on the thermal output of the engine exhaust. To better demonstrate the filtration efficiency, Table 9 outlines each active device and its respective efficiency, with highlighted maximum values in red and minimum reduction values in blue, a format that is carried throughout the tables in this study. This table does not consider the passive runs since this investigation is not concerned with the comparison of active operation to that of passive filtration. Passive filtration is discussed separately in Section 5.1.9. In Table 9 device 4 active with a DOC and new regeneration strategy had the highest reduction of PM from the baseline for modes 1 at -91.85%, 2 at -85.28%, 3 at -86.10% and 4 at -88.68%. Device 3 active with a DOC had the greatest reduction from baseline in modes 5 at -96.14%, 6 at -89.91%, and 7 at -88.90%. The lowest percent reduction from baseline occurred with device 2 and 3 active and for mode 6 device 4 active with a DOC achieved a -34.78% reduction from baseline. Device 2 active had reduction of -55.83% in mode 1, -48.14% in mode 3, and -58.29% in mode 5. Device 3 active had a reduction of -52.16% from baseline in mode 2, -46.38% in mode 4 and -60.03% in mode 7.

Table 9: PM Brake Specific Difference from Baseline, Active Runs Only

	Mode	1	2	3	4	5	6	7
D1 A	PM	-57.61%	-61.71%	-55.56%	-58.40%	-63.36%	-56.63%	-62.86%
D2 A		-55.83%	-55.43%	-48.14%	-56.01%	-58.29%	-61.13%	-67.25%
D3 A		-86.53%	-52.16%	-50.64%	-46.38%	-92.23%	-60.54%	-60.03%
D3 A DOC		-91.48%	-73.67%	-78.42%	-77.89%	-96.14%	-89.91%	-88.90%
D3 A DOC NR		-91.53%	-79.97%	-83.08%	-83.30%	-93.16%	-87.17%	-85.76%
D4 A		-79.42%	-69.45%	-60.67%	-62.32%	-91.65%	-73.68%	-72.19%
D4 A DOC		-61.76%	-70.70%	-76.87%	-73.24%	-88.35%	-34.78%	-70.16%
D4 A DOC NR		-91.85%	-85.28%	-86.10%	-88.68%	-95.04%	-81.32%	-84.82%
D5 A		-87.13%	-69.66%	-62.67%	-62.75%	-92.57%	-71.00%	-66.68%
D5 A DOC		-91.60%	-84.35%	-74.06%	-75.09%	-95.88%	-81.36%	-82.79%

5.1.3 Modal Hydrocarbon Results, Active Only

The destruction of HC occurs inside the DPF. It is theorized that the HCs are absorbed onto particles of PM and are trapped with the PM in the filter media and subsequently are oxidized when the DPF regenerates, however the gas phase HCs are forced through the filter media where the PM which is made up mostly of carbon, bonds with some of the HCs and traps them. The utilization of a DOC also means that HCs in the exhaust stream are turned into CO_2 and water. The resulting reduction in HCs from the exhaust stream is shown in Figure 12. The results show that the configurations that utilized a DOC had a much greater increase in CO_2 from baseline than that of DPFs that were not equipped with a DOC. The average increase in CO_2 from baseline was 0.18% for non-DOC equipped DPFs and 0.38% for DPFs with a DOC. Figure 12 below shows the graphical results of the HC analysis. The HC reduction is shown in Table 10 with the maximum and minimum reductions highlighted in red and blue, respectively. This chart shows that only DPFs utilizing a DOC achieved a maximum HC reduction for this data set and in turn only DPFs without a DOC were at the minimum reduction levels. In general, a DPF with a DOC results in a HC reduction of at least 75% while a DPF without a DOC only results in a maximum reduction of 19.60% showed by device 4 active in mode 7.

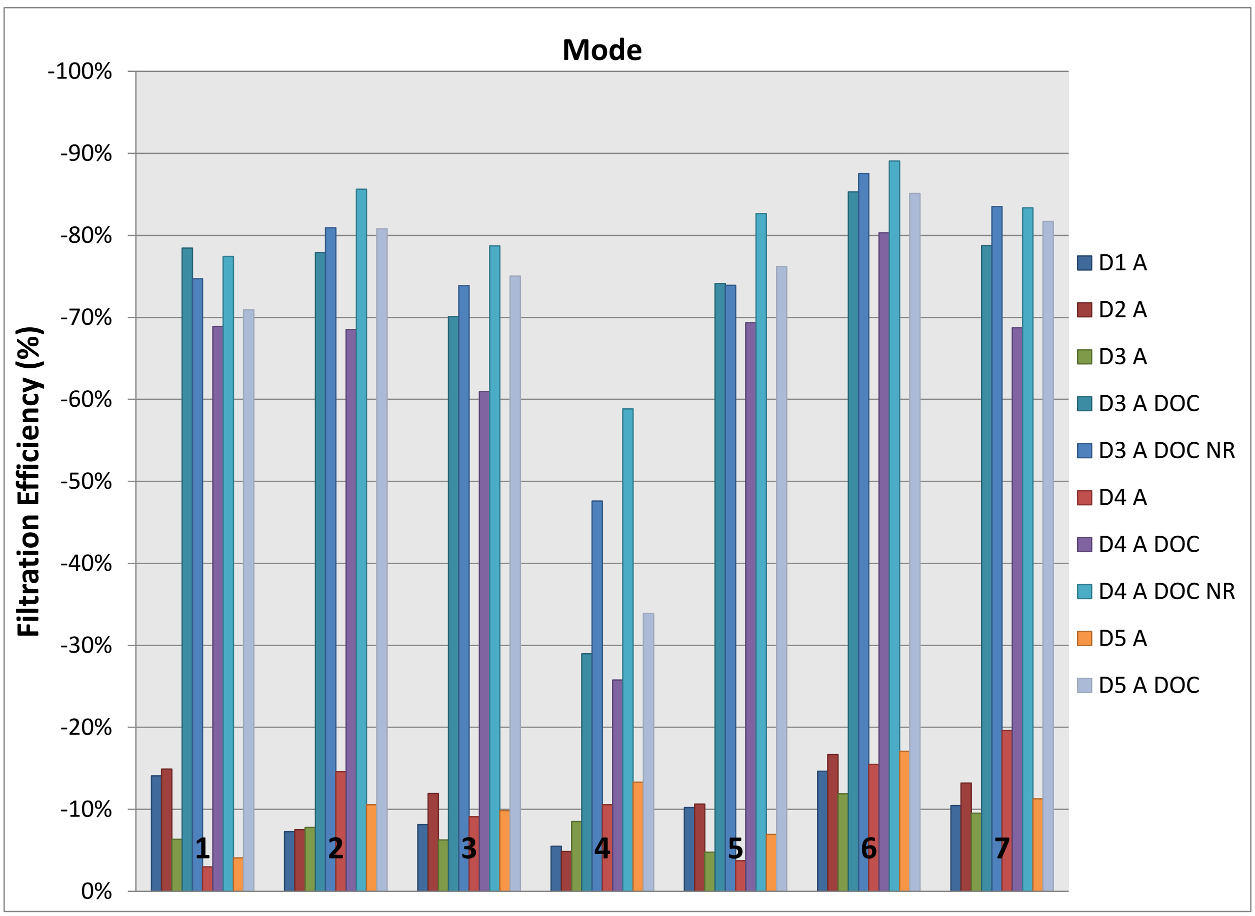

Figure 12: Brake Specific Modal HC Reduction Efficiency, Active Runs Only

Table 10: HC Brake Specific Difference from Baseline, Active Runs Only

	Mode	1	2	3	4	5	6	7
D1 A	HC	-14.08%	-7.29%	-8.13%	-5.48%	-10.21%	-14.64%	-10.46%
D2 A		-14.90%	-7.52%	-11.93%	-4.84%	-10.65%	-16.67%	-13.20%
D3 A		-6.35%	-7.78%	-6.27%	-8.52%	-4.77%	-11.89%	-9.51%
D3 A DOC		-78.46%	-77.90%	-70.10%	-28.97%	-74.12%	-85.31%	-78.78%
D3 A DOC NR		-74.72%	-80.94%	-73.89%	-47.61%	-73.90%	-87.54%	-83.52%
D4 A		-2.97%	-14.59%	-9.08%	-10.56%	-3.72%	-15.48%	-19.60%
D4 A DOC		-68.89%	-68.53%	-60.96%	-25.77%	-69.34%	-80.31%	-68.74%
D4 A DOC NR		-77.44%	-85.62%	-78.72%	-58.83%	-82.67%	-89.08%	-83.36%
D5 A		-4.07%	-10.55%	-9.85%	-13.32%	-6.93%	-17.08%	-11.29%
D5 A DOC		-70.92%	-80.80%	-75.05%	-33.89%	-76.20%	-85.11%	-81.70%

5.1.4 Modal Carbon Monoxide Results, Active Only

Modal CO results are represented graphically in Figure 13. Device 1 reduced CO on modes 2 at -18.82%, 6 at -1.96% and 7 at -0.36%; however, it had more CO than the baseline in modes 1 at 12.87%, 3 at 1.46%, 4 at 6.70%, and 5 at 6.77%. Device 2 reduced CO on modes 2 at -2.19%, and 5 at -11.55%, but this device also increased CO production on modes 1 by 0.32%, 3 at 32.08%, 4 at 6.50%, 6 at 9.96%, and 7 at 3.55%. This device had the largest increase of CO on mode 3 of any of the other devices. Device 3, with the addition of a DOC, reduced CO for every mode. Device 4 active, with a DOC, had the highest increase of CO from baseline in mode 6 at 237%. All the other iterations of device 4 also produced more CO than the baseline in this mode. Device 4 active without a DOC had the highest increase of CO from baseline in mode 1 at 37.53%. Device 5 shows the impact that a DOC can have on the production of CO. Device 5 with a DOC achieved reduction across all the modes, whereas without a DOC an increase of CO from baseline is witnessed on modes 1 at 9.1%, 2 at 38.22%, 3 at 0.83% and 6 at 68.12%. Even when device 5 without a DOC reduced CO it is an order of magnitude smaller than that of the reduction achieved with a DOC. Table 10 shows a numerical representation of the data from Figure 13. In this Table, device 3 active with a DOC achieved maximum CO reduction in modes 1 at -80.87%, 3 at -89.08%, and 6 at -53.27%; this device maintained the maximum reduction across three modes which is more than any of the other devices. From Table 11 it is also clear that only DOC equipped devices achieved a maximum reduction for each mode. This is because a DOC oxidizes CO and turns it into CO_2.

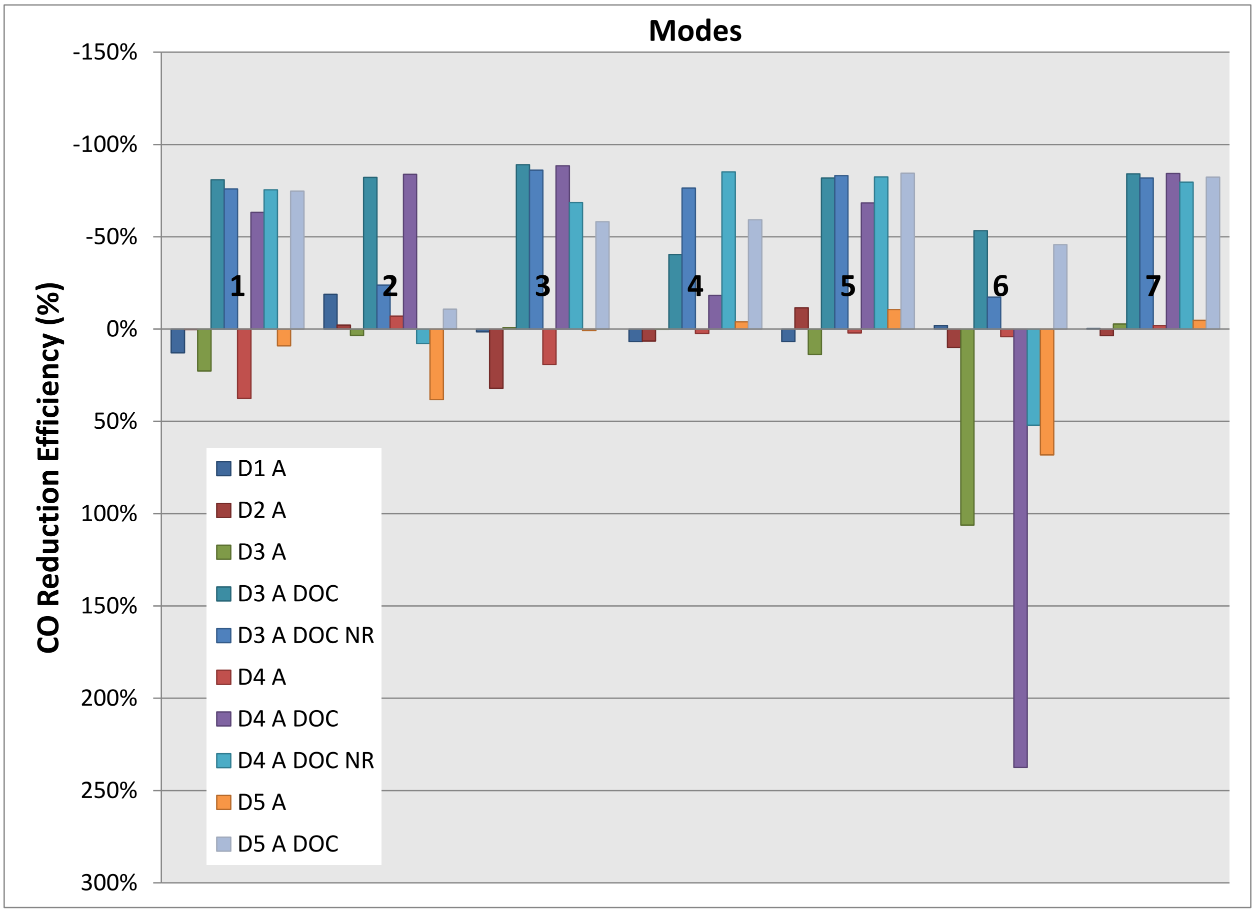

Figure 13: Brake Specific CO Reduction Efficiency, Active Runs Only

Table 11: CO Brake Specific Difference from Baseline, Active Runs Only

	Mode	1	2	3	4	5	6	7
D1 A	CO	12.87%	-18.82%	1.46%	6.70%	6.77%	-1.96%	-0.36%
D2 A		0.32%	-2.19%	32.08%	6.50%	-11.55%	9.96%	3.55%
D3 A		22.70%	3.42%	-0.83%	0.11%	13.74%	106.16%	-2.71%
D3 A DOC		-80.87%	-82.25%	-89.08%	-40.41%	-81.88%	-53.27%	-84.11%
D3 A DOC NR		-75.92%	-23.87%	-86.13%	-76.42%	-83.17%	-17.30%	-81.81%
D4 A		37.53%	-7.04%	19.20%	2.35%	2.11%	4.11%	-1.88%
D4 A DOC		-63.29%	-83.83%	-88.49%	-18.22%	-68.34%	237.44%	-84.27%
D4 A DOC NR		-75.50%	7.75%	-68.53%	-85.13%	-82.45%	52.05%	-79.56%
D5 A		9.10%	38.22%	0.83%	-3.87%	-10.54%	68.12%	-4.73%
D5 A DOC		-74.74%	-10.80%	-58.19%	-59.22%	-84.44%	-45.74%	-82.31%

5.1.5 Modal Carbon Dioxide Results, Active Only

The results for CO_2 are represented graphically in Figure 14. In mode 1, an increase in CO_2 was witnessed for all devices with one exception, device 3 active which showed a reduction of less than 1%. The largest increase in CO_2 is shown in mode 4 where device 4 active increased CO_2 levels by 8% over the baseline. Modes 1 and 4 were the only modes where increased CO_2 for any device was above 2%. Device 3 active was the only DPF that reduced CO_2 over all modes and it even had the highest reduction in modes 1, 2, 3, 4, 5, and 6; the values for these modes, respectively, are -0.54%, -3.83%, -3.66%, -2.40%, -0.76%, and -1.18%. Mode 7 had slightly lower reduction percentage than that of device 4 active with a DOC. Table 12 shows the numerical results from the CO_2 findings. It is clear that in regards to CO_2 the greatest reduction comes from device 3 active. Device 2 active also had the worst characteristics, being that it increased CO_2 production for nearly every mode at the highest levels recorded for the devices.

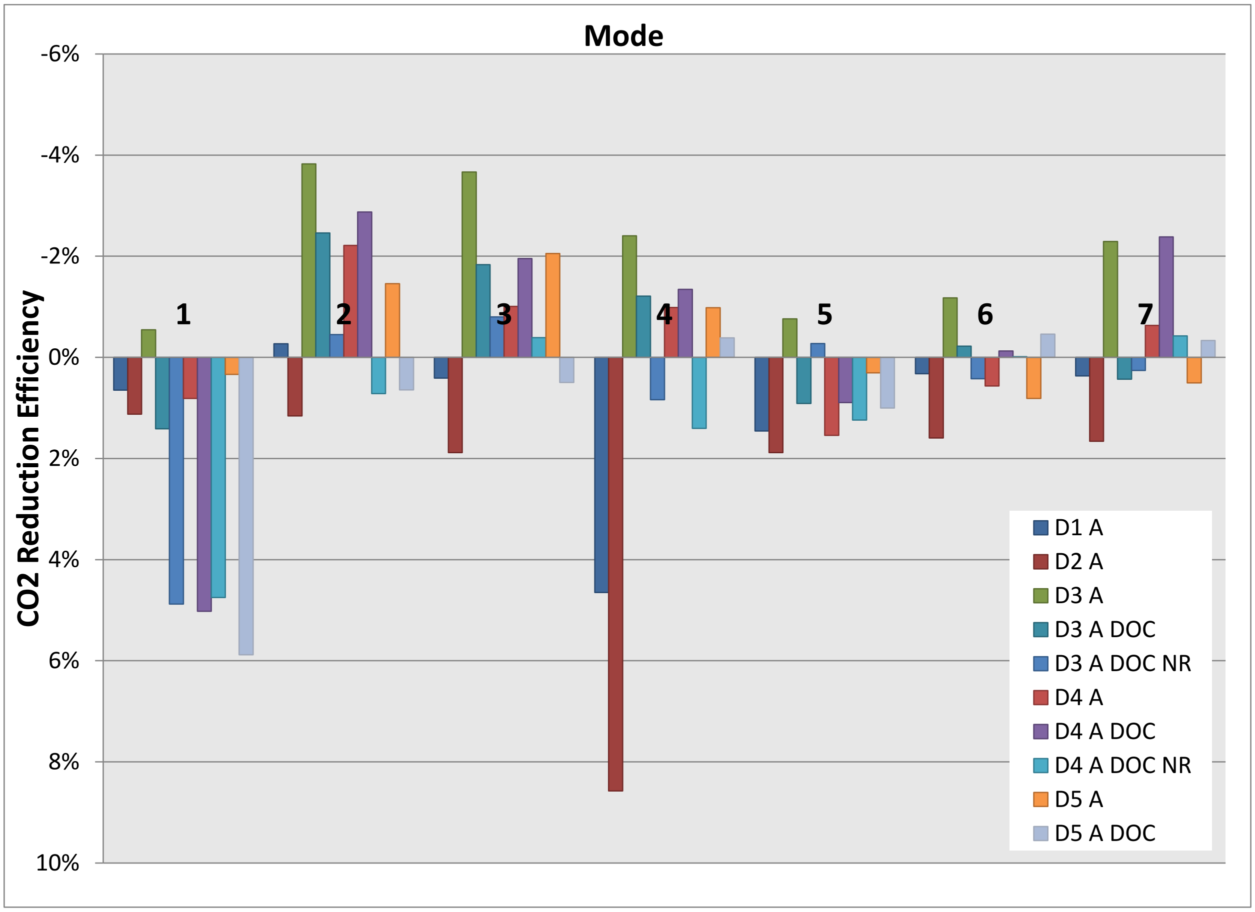

Figure 14: Brake Specific CO_2 Reduction Efficiency, Active Runs Only

Table 12: CO_2 Brake Specific Difference from Baseline, Active Runs Only

	Mode	1	2	3	4	5	6	7
D1 A	CO2	0.65%	-0.27%	0.41%	4.65%	1.45%	0.33%	0.37%
D2 A		1.12%	1.16%	1.88%	8.57%	1.88%	1.59%	1.66%
D3 A		-0.54%	-3.83%	-3.66%	-2.40%	-0.76%	-1.18%	-2.29%
D3 A DOC		1.41%	-2.46%	-1.83%	-1.21%	0.91%	-0.22%	0.43%
D3 A DOC NR		4.88%	-0.45%	-0.80%	0.84%	-0.27%	0.42%	0.26%
D4 A		0.81%	-2.21%	-1.01%	-0.99%	1.54%	0.56%	-0.63%
D4 A DOC		5.02%	-2.88%	-1.95%	-1.35%	0.90%	-0.13%	-2.38%
D4 A DOC NR		4.75%	0.72%	-0.39%	1.40%	1.24%	-0.01%	-0.42%
D5 A		0.34%	-1.46%	-2.05%	-0.98%	0.31%	0.81%	0.51%
D5 A DOC		5.88%	0.64%	0.50%	-0.39%	1.00%	-0.46%	-0.34%

5.1.6 Modal Oxides of Nitrogen Results, Active Only

Device 1 had an increase in NOx production in modes 1, 2, 3, and 4 but it reduced NOx in modes 5, 6, and 7 as shown in Figure 15. Device 2 active had increased NOx across all modes. In mode 4 it increased NOx by over 7%. Device 3 active showed reduction of NOx in all modes except mode 5. This device also had the highest NOx reduction values for modes 1, 2, 6, and 7. Device 3 active with a DOC showed an increased production of NOx in modes 1 at 1.9% and 2 at 0.27% where as previously, without a DOC, reductions above 2% were recorded. Device 3 active with the new regeneration strategy increased the NOx reduction in mode 4 above that of the unaltered device configuration; however, it reduced NOx in modes 3, 6, and 7. Device 4 active showed excess production of NOx for modes 2 to 6 while this device only reduced NOx in modes 1 and 7. Device 4 active with a DOC showed an increase in production of NOx in mode 1, however modes 2, 3, 6, and 7 have reduction values of -1.24%, -3.59%, -0.65%, and -0.76%, respectively, and the NOx in modes 4 and 5 were decreased. Device 4 active with a new regeneration strategy increased NOx in modes 1 by 0.07% and 5 by 1.59% as well as achieving reduction in mode 4 where previously none existed. Device 5 active had the highest NOx production for mode 5. Device 5 active with a DOC increased the production of NOx in mode 1 by 1.96% as well as reducing the filtration efficiency in mode 2 by 0.26%. In modes 2, 3, 4, and 6 there was greater reduction of NOx. Table 13 shows the brake specific percent difference from baseline for NOx. Device 2 active exhibited no NOx reduction in any mode while mode 4 achieved the greatest increase of NOx from baseline with a value of 7.67%. Device 3 had the largest number of maximum reductions across the modes. Mode 3 from device 3 had the highest value (-3.59%) of reduction from baseline of any of the other modes for any other device. Note that device 1 active, device 2 active and device 4 active also exhibited increases of NOx from baseline for different modes on the order of 1% to 3%.

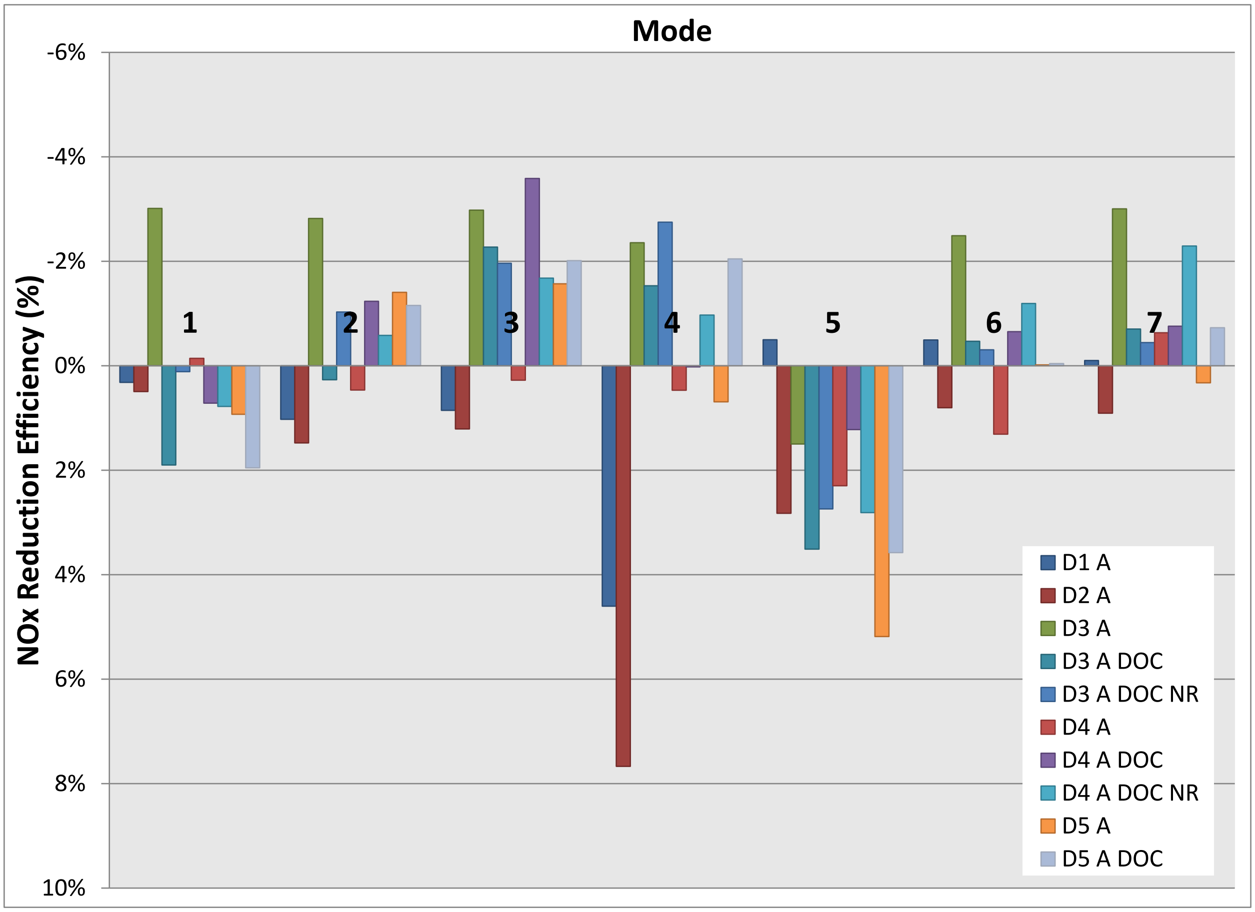

Figure 15: Brake Specific NOx Reduction Efficiency, Active Runs Only

Table 13: NOx Brake Specific Difference from Baseline, Active Runs Only

	Mode	1	2	3	4	5	6	7
D1 A	Nox	0.32%	1.02%	0.85%	4.60%	-0.50%	-0.49%	-0.10%
D2 A		0.49%	1.48%	1.21%	7.67%	2.82%	0.80%	0.91%
D3 A		-3.02%	-2.82%	-2.98%	-2.35%	1.50%	-2.49%	-3.01%
D3 A DOC		1.90%	0.27%	-2.27%	-1.53%	3.51%	-0.47%	-0.70%
D3 A DOC NR		0.11%	-1.03%	-1.96%	-2.75%	2.74%	-0.30%	-0.44%
D4 A		-0.14%	0.47%	0.28%	0.47%	2.30%	1.31%	-0.63%
D4 A DOC		0.71%	-1.24%	-3.59%	0.02%	1.22%	-0.65%	-0.76%
D4 A DOC NR		0.78%	-0.58%	-1.68%	-0.97%	2.81%	-1.20%	-2.29%
D5 A		0.93%	-1.41%	-1.57%	0.69%	5.18%	-0.02%	0.33%
D5 A DOC		1.96%	-1.15%	-2.01%	-2.05%	3.58%	-0.04%	-0.73%

5.1.7 Modal Nitrogen Monoxide Results, Active Only

Results for NO are represented graphically in Figure 16. Device 1 showed an increase in NO for all modes with the exception of mode 5 where there was a small reduction of -0.215%. Device 2 showed an increase in NO for all modes and even had the largest values for modes 2 at 3.24%, 3 at 6.10%, and 7 at 3.77%. Device 3 active showed small reductions for modes 1, 2, 6, and 7 with values of -0.67%, -0.74%, -1.04%, and-0.74%, respectively, it also showed increases from baseline over modes 3, 4, and 5 at 0.81%, 2.78%, and 2.32%, respectively. Device 3 active with a DOC exhibited a reduction in NO for modes 2, 3, 5, 6, and 7 at -17.61%, -11.91%, -2.02%, -16.13%, and -13.19%, respectively. Of these reductions modes 2, 3, 5, and 6 were the highest reduction of NO for the tested DPFs. Device 3 active with a new regeneration strategy increased NO from baseline in mode 1 and decreased the rate at which it had reduced NO from baseline slightly for all other modes where the new regeneration strategy was not implemented. Device 4 active showed an increase of NO from baseline for all modes. Device 4 active with a DOC had the maximum value for increased NO from baseline on mode 4 at 13.58%. The addition of the DOC increased NO for mode 1 by 0.23% and 4 by 6.65% and reduced the increase from baseline in all other modes and even achieved reduction in modes 2 at -2.52% and 6 at -3.29%. Device 4 active with a new regeneration strategy had increased NO for modes 1 and 4 past the other iterations of this device, however, large reductions are shown in modes 2 at -4.12%, 3 at-7.13%, 6 at -14.69%, and 7 at -17.82%. It is important to note that mode 7 reduction from baseline for this device was the largest reduction amongst any of the modes or devices. Device 5 active produced an increase of NO from baseline across all modes. Device 5 active with a DOC resulted in NO reduction in modes 2, 3, 6, and 7 with corresponding values of -4.90%, -8.56%, -15.75%, and -14.57% while increasing levels of NO for modes 1at 3.97% and 4 at 13.23%. For mode 5 the NO was reduced between baseline and after treatment testing. Table 14 shows these results.

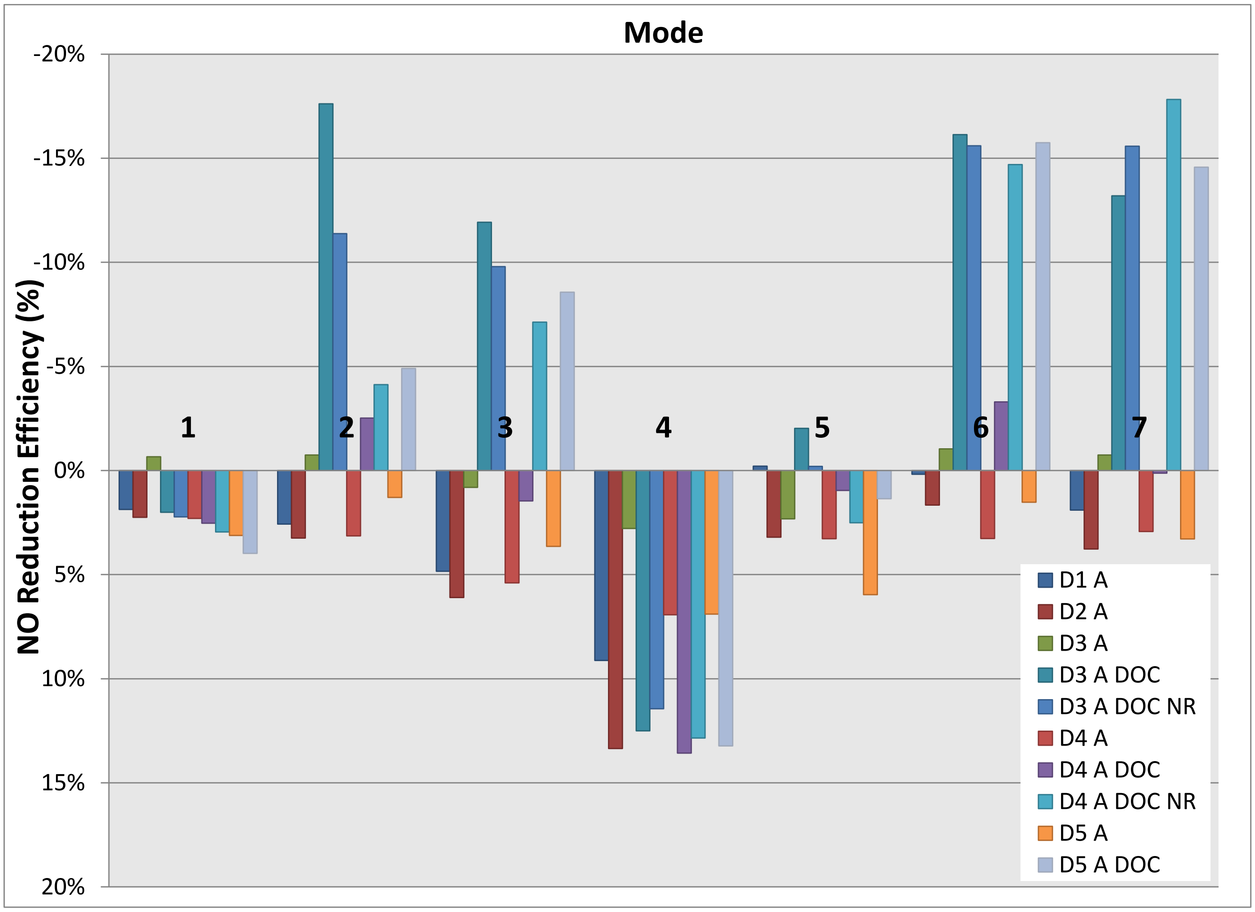

Figure 16: Brake Specific NO Reduction Efficiency, Active Runs Only

Table 14: NO Brake Specific Difference from Baseline, Active Runs Only

	Mode	1	2	3	4	5	6	7
D1 A	NO	1.87%	2.57%	4.84%	9.12%	-0.21%	0.18%	1.90%
D2 A		2.25%	3.24%	6.10%	13.35%	3.21%	1.66%	3.77%
D3 A		-0.67%	-0.74%	0.81%	2.78%	2.32%	-1.04%	-0.74%
D3 A DOC		2.01%	-17.61%	-11.92%	12.50%	-2.02%	-16.13%	-13.19%
D3 A DOC NR		2.22%	-11.38%	-9.80%	11.44%	-0.20%	-15.60%	-15.58%
D4 A		2.30%	3.14%	5.40%	6.93%	3.28%	3.27%	2.93%
D4 A DOC		2.53%	-2.52%	1.45%	13.58%	0.95%	-3.29%	0.12%
D4 A DOC NR		2.95%	-4.12%	-7.13%	12.85%	2.51%	-14.69%	-17.82%
D5 A		3.12%	1.29%	3.65%	6.89%	5.96%	1.52%	3.29%
D5 A DOC		3.97%	-4.90%	-8.56%	13.23%	1.35%	-15.75%	-14.57%

5.1.8 Passive Analysis

This section investigates the operation characteristics of some of the DPFs under a passive operation. The filtration efficiencies should be higher due to the lack of regeneration. This passive operation is done to determine any attributes that these devices may have when regeneration does not occur over the course of the 8- mode test.

It can be seen that the higher PM filtration efficiencies are associated with filters that are coupled with a DOC in Figure 17. Device 3 with a DOC showed the highest filtration efficiencies achieving over 90% filtration over modes 1 through 6 and near 90% on mode 7. Device 3 achieved over 95% filtration efficiency over mode 5 but over the remainder of the modes its efficiency was below 90%. Device 4 had the lowest filtration levels for modes 2, 3, 5, 6, and 7 with filtration below 75%; mode 1 exhibited approximately 80% and mode 4 at 75% reductions. It is also important to note that device 3 had no data for mode 7 because the DTC failed to change modes successfully and is thus not comparable for that mode. Table 15 shows that device 3 passive with a DOC had the highest PM filtration efficiency across all modes. It is also clear that Device 4 passive had the lowest reduction of PM with its maximum value in mode 1 at 80.51% reduction and its minimum reduction in mode 6 at 65.8%.

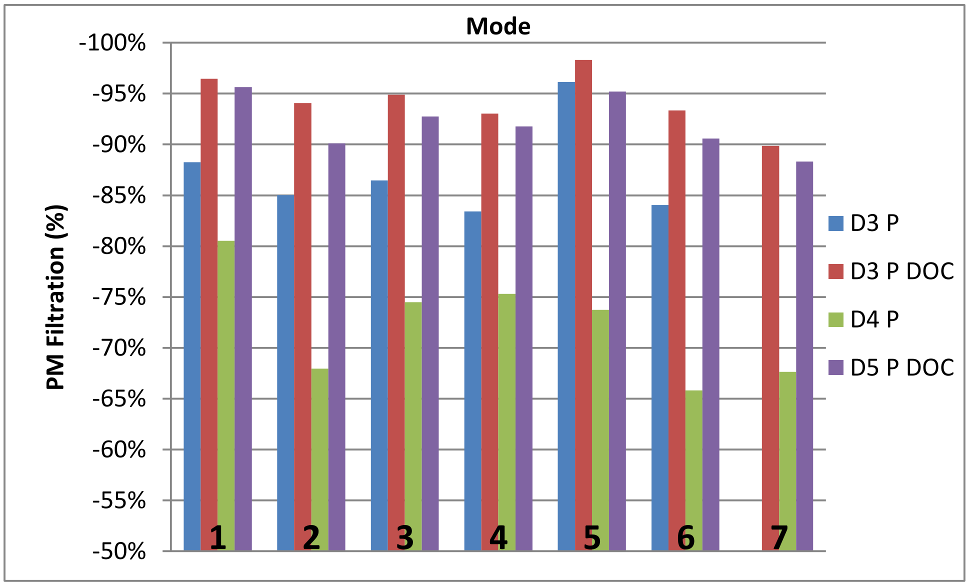

Figure 17: Brake Specific PM Reduction Efficiency, Passive Runs Only

Table 15: PM Brake Specific Difference from Baseline, Passive Runs Only

	Mode	1	2	3	4	5	6	7
D3 P	PM	-88.24%	-85.03%	-86.47%	-83.42%	-96.15%	-84.04%	-
D3 P DOC		-96.46%	-94.07%	-94.89%	-93.03%	-98.30%	-93.36%	-89.85%
D4 P		-80.51%	-67.96%	-74.49%	-75.30%	-73.75%	-65.80%	-67.65%
D5 P DOC		-95.64%	-90.10%	-92.75%	-91.77%	-95.19%	-90.58%	-88.32%

Hydrocarbon reduction occurred for all the devices. Figure 18 shows the graphical representation for all the percent reductions from baseline. Both devices equipped with a DOC had the largest reductions in HC. Device 3 passive with a DOC had the largest reduction across all modes. Device 3 passive had greater HC reductions for modes 2, 4, 5, and 6 than that of device 4 passive. Table 16 shows the numerical representation of the HC reduction. Device 3 passive with a DOC had the greatest HC reduction in modes 2 through 7. Device 5 passive with a DOC had the greatest HC reduction in modes 1 and 2. Device 4 passive had the least reduction across modes 2 through 7 with mode 1 being dominated by device 3 passive.

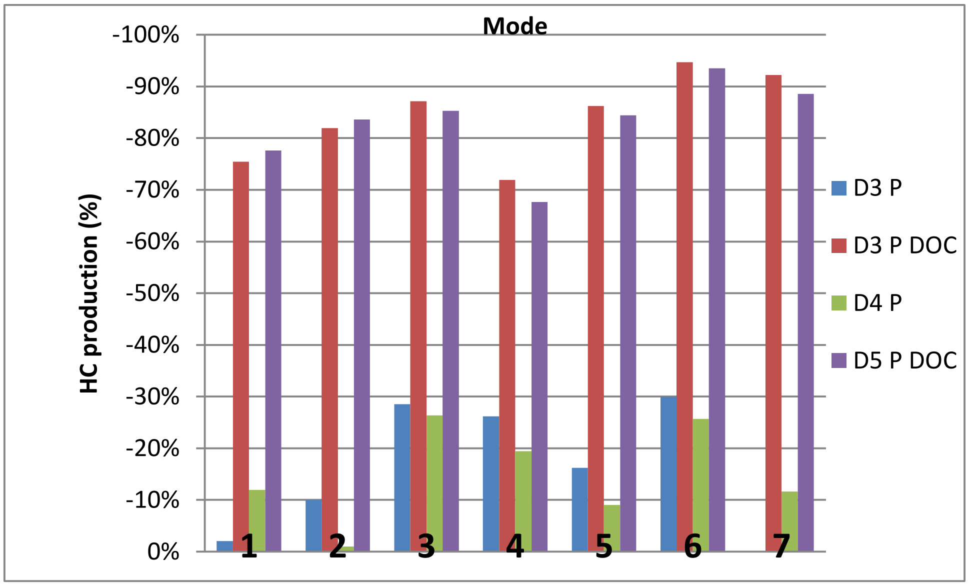

Figure 18: Brake Specific HC Reduction Efficiency, Passive Runs Only

Table 16: HC Brake Specific Difference from Baseline, Passive Runs Only

	Mode	1	2	3	4	5	6	7
D3 P	HC	-2.01%	-10.04%	-28.52%	-26.18%	-16.19%	-30.00%	-
D3 P DOC		-75.44%	-81.95%	-87.16%	-71.90%	-86.22%	-94.67%	-92.25%
D4 P		-11.92%	-0.97%	-26.35%	-19.44%	-9.05%	-25.71%	-11.61%
D5 P DOC		-77.63%	-83.65%	-85.30%	-67.66%	-84.43%	-93.50%	-88.57%

Reduction of CO occurred for device 3 and 5 with a DOC as illustrated in Figure 19. Device 3 passive had increased levels of CO for modes 1, 2, 3, 4, and 6. This device only had reduction in mode 5. Device 4 passive had increased production of CO for modes 1, 2, and 6. Device 5 passive with a DOC had the maximum reduction of CO for all modes. Device 3 passive with a DOC shadowed that of device 5 passive with a DOC and in modes 1, 4, and 5 as they were similar in percentage CO reduction. Table 16 shows the fractions of difference between device 3 and 5 passive with a DOC. Device 5 clearly exhibited the largest reductions of

CO across all modes. Device 3 passive showed that it had both the largest production and least reduction across more modes than that of device 4 passive.

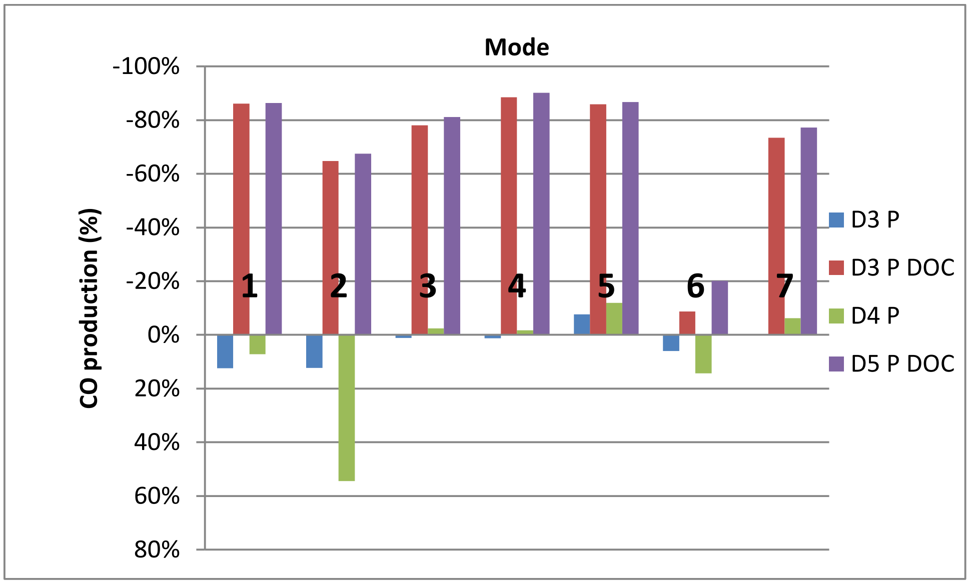

Figure 19: Brake Specific CO Reduction Efficiency, Passive Runs Only

Table 16: CO Brake Specific Difference from Baseline, Passive Runs Only

	Mode	1	2	3	4	5	6	7
D3 P	CO	12.44%	12.28%	1.10%	1.30%	-7.66%	6.03%	-
D3 P DOC		-86.13%	-64.78%	-78.04%	-88.50%	-85.96%	-8.70%	-73.48%
D4 P		7.21%	54.52%	-2.47%	-1.73%	-11.90%	14.33%	-6.20%
D5 P DOC		-86.36%	-67.47%	-81.14%	-90.14%	-86.74%	-20.12%	-77.28%

Figure 20 illustrates that the production of CO_2 occurred for all passive operations of the device with the exception of mode 1 for device 3 passive. Device 3 passive also had the least CO_2 production across all modes with the exception of modes 5 and 7 for which data does not exist because the DTC failed to switch properly from mode 4 to 5 and also 6 to 7. The largest production of CO_2 occurred with device 3 passive with a DOC with the exception of mode 1 where the largest production of CO_2 came from device 5 passive with a DOC. The largest production of CO_2 for any mode occurred on devices equipped with a DOC. In mode 5, device 3 passive with a DOC showed an increase in CO_2 larger than 10% and device 5 passive with a DOC yields CO_2 production larger than 8%. Table 18 further demonstrates the CO_2 data and the production and reduction associated with each device. Again it was demonstrated numerically that device 3 passive had the least CO_2 production and that device 3 passive with a DOC had the largest number of modes demonstrating increased production for all modes except mode 1.

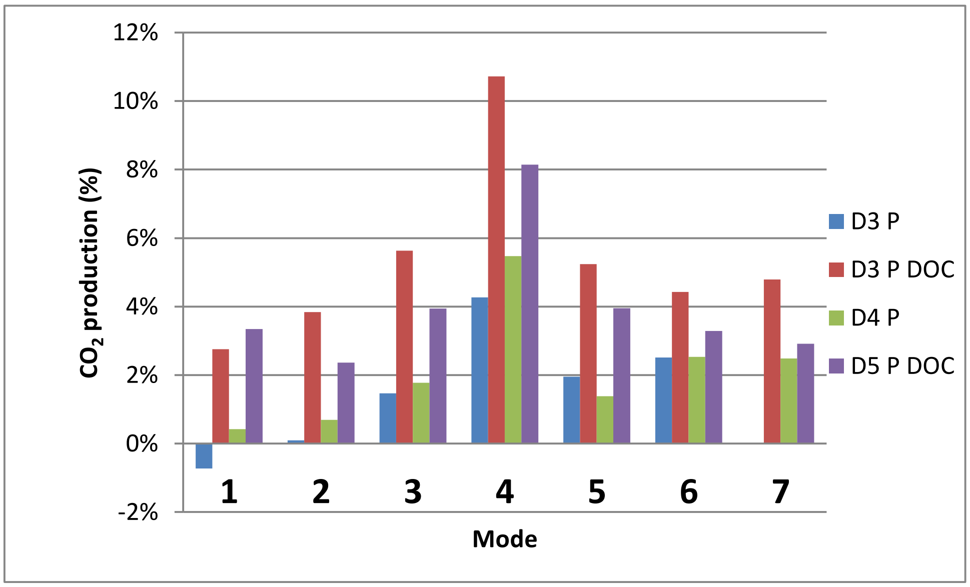

Figure 20: Carbon Dioxide Percent Reduction

Table 18: CO_2 Brake Specific Difference from Baseline, Passive Runs Only

	Mode	1	2	3	4	5	6	7
D3 P	CO2	-0.73%	0.10%	1.47%	4.27%	1.95%	2.52%	-
D3 P DOC		2.76%	3.84%	5.64%	10.72%	5.24%	4.42%	4.79%
D4 P		0.42%	0.69%	1.78%	5.47%	1.38%	2.53%	2.49%
D5 P DOC		3.34%	2.37%	3.94%	8.14%	3.95%	3.29%	2.91%

Reduction of NOx only occurs in modes 1, 2, and 3 as shown graphically in Figure 21. Device 3 passive had the largest reduction of NOx at -3.43%. Device 3 passive also had the largest production of NOx in modes 2 and 6. Device 3 passive had the largest production of

NOx of all the modes producing over 12% in mode 4; it is also the largest producer in modes 3, 5, and 7. Device 4 passive had the largest reduction in mode 2 as well as the largest production in mode 2. This DPF also produced the least amount of NOx for modes 4, 6, and 7. Device 5 passive with a DOC had the largest NOx reduction at mode 3. Table 19 shows that device 4 passive had the greatest reduction and smallest increase from baseline of NOx over more modes than any of the other devices investigated. Device 3 passive with a DOC had the largest dispersion of NOx production over more modes than that of the other devices. The DOC seems to have little effect on the trends regarding production and reduction of NOx

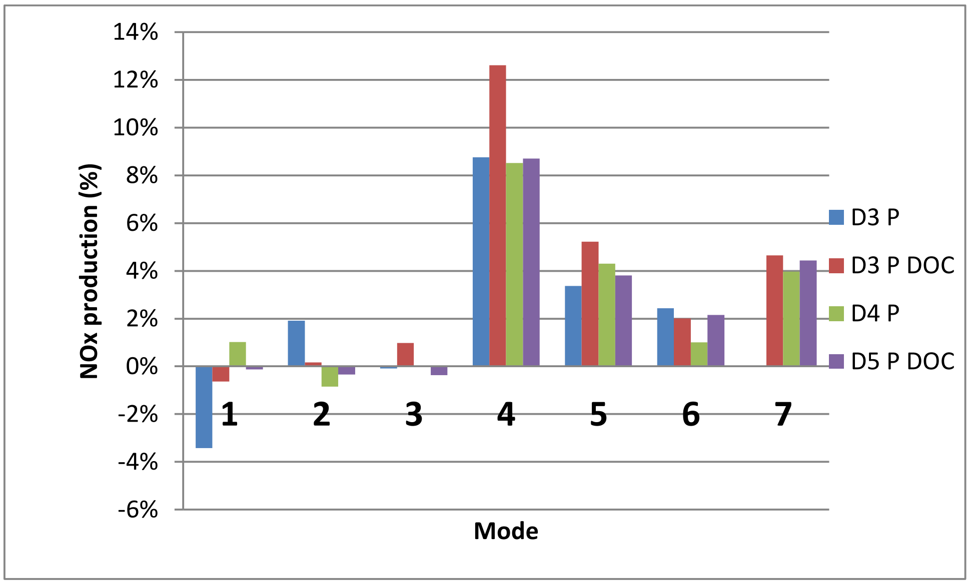

Figure 21: NOx Percent Reduction

Table 19: NOx Brake Specific Difference from Baseline, Passive Runs Only

	Mode	1	2	3	4	5	6	7
D3 P	NOx	-3.43%	1.91%	-0.09%	8.76%	3.37%	2.43%	-
D3 P DOC		-0.63%	0.17%	0.98%	12.61%	5.22%	2.01%	4.65%
D4 P		1.02%	-0.84%	-0.01%	8.52%	4.30%	1.01%	3.97%
D5 P DOC		-0.13%	-0.34%	-0.37%	8.71%	3.81%	2.15%	4.44%

NO reduction only occurred in modes 1, 6, and 7 as shown in Figure 22 below. Device 3 passive had the largest reduction for mode 1; it also had the largest increase from baseline in modes 2, 3, and 6. Device 3 passive with a DOC had the least amount of increase of NO in mode 2 and the largest increase of NO in mode 4, and 5. This device also had the largest reduction of all devices in mode 7 with a reduction over 10%. Device 4 passive had the largest increase from baseline of NO in modes 1 and 7. Device 5 passive with a DOC had the lowest increase from baseline of NO in modes 3 and 5 as well as the largest reduction in mode 6. The addition of a DOC seems to only to affect operation in modes 6 and 7 where devices equipped with a DOC exhibit NO reduction beyond that of the devices that are not equipped with a DOC. The numerical results of NO production are shown below in Table 20. Device 5 passive with a DOC had the least production and highest reduction among more modes than the other devices. Device 3 passive had the largest dispersion of NO production among the modes, which is also coupled with one instance of maximum reduction and one instance of minimum production.

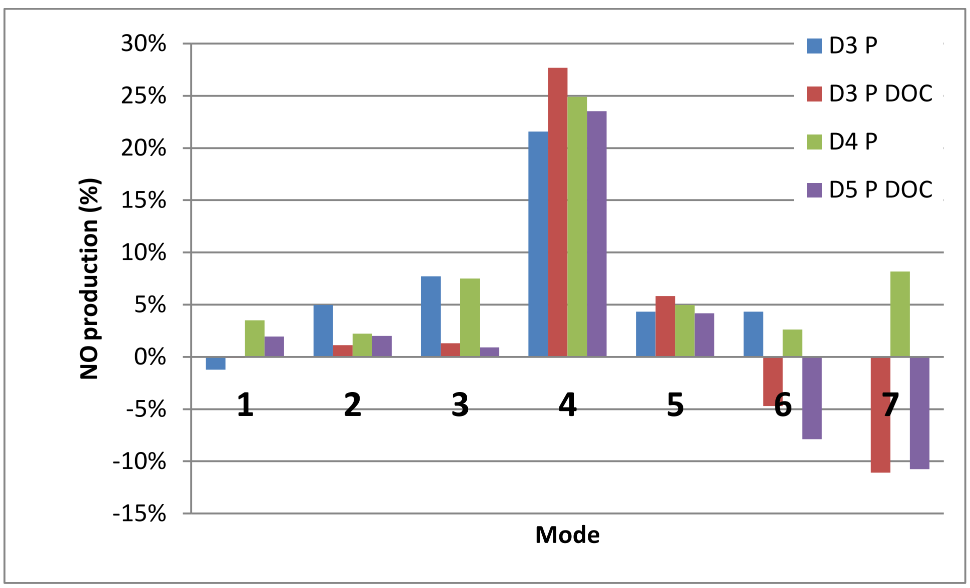

Figure 22: Nitrogen Dioxide Percent Reduction

Table 20: NO Brake Specific Difference from Baseline, Passive Runs Only

	Mode	1	2	3	4	5	6	7
D3 P	NO	-1.23%	4.97%	7.73%	21.59%	4.33%	4.32%	-
D3 P DOC		-0.08%	1.11%	1.31%	27.68%	5.81%	-4.70%	-11.09%
D4 P		3.52%	2.23%	7.52%	24.92%	4.96%	2.60%	8.16%
D5 P DOC		1.96%	2.00%	0.90%	23.54%	4.17%	-7.89%	-10.76%

The passive analysis of these DPFs that are traditionally operated with an active control strategy has given insight into the potential filtration efficiencies that can be achieved by these devices. This analysis also showed the effect that passive operation had on the emissions characteristics. Further insight into the effect of passive operation of the DPF coupled with a DOC was also achieved.

5.2 Composite Analysis

5.2.1 Evaluation of 8-mode Composite and TRU 4-mode Composite Results

The 8-mode composite is the standard evaluation for a TRU DPF. This composite analysis gives weighting factors to each of the modes to better capture the actual operation of a DPF in real world conditions by weighting regimes of operation with larger impact on the composite result than regimes that are not indicative of TRU operation. The weighting factors for the 8 mode composite are 0.15 for modes 1, 2, 3, and 8 while modes 4, 5, 6, and 7 are 0.1 [16]. The TRU composite 4-mode analysis is a specific adaptation of the 8-mode test data that is performed for TRU units and on modes 2, 3, 6, and 7. The weighting factor for the composite 4 mode is 0.25 for these modes [17]. This is done because although a TRU unit is on the road and requires regulations that meet the on road standards set out by the EPA and CARB, it does not act as a traditional on-road engine. Due to the nature of operation of a TRU unit's engine a composite of the results of the ISO 8178 cycle are used to evaluate the emissions characteristics of the engine. Table 21 shows the composite results for all the active devices analyzed in this study. It is clear from the findings that device 4 with a DOC and a new regeneration strategy had the largest reduction of PM at -89.33%. This device also showed considerable reduction in HC at -61.10%, as well as CO at -56.34% and NO at-67.17%. This data also showed that device 2 achieved the lowest filtration efficiency at -51.17%. It is also important to note that device 4 without a DOC nor a new regeneration strategy compared poorly to the device with a DOC and new regeneration strategy with a difference in HC reduction of 66.8%. The implementation of a DOC and a new strategy pushed this device's PM filtration efficiency over 14% higher than the device without a DOC.

Table 21: 8-mode Composite Emissions Analysis, Active Only

8 mode composite												
	D1 A	D2 A	D3 A	D3 A DOC	D3 A DOC NR	D4 A	D4 A DOC	D4 A DOC NR	D5 A	D5 A DOC	min	max
HC (g/bhphr)	-11.02%	-13.00%	-8.10%	-68.86%	-71.97%	-9.71%	-61.10%	-76.51%	-9.85%	-68.99%	-8.10%	-76.51%
CO (g/bhphr)	4.43%	0.74%	14.03%	-74.96%	-69.18%	15.99%	-56.34%	-63.19%	5.19%	-64.66%	15.99%	-74.96%
CO2 (g/bhphr)	0.49%	1.61%	-2.13%	-0.34%	1.37%	-0.08%	0.32%	1.59%	-0.27%	1.76%	1.76%	-2.13%
NOx (g/bhphr)	0.13%	1.43%	-1.95%	0.66%	0.21%	0.85%	0.10%	0.27%	1.09%	0.83%	1.43%	-1.95%
NO (g/bhphr)	1.83%	3.56%	0.24%	-7.91%	-6.34%	3.64%	1.04%	-4.13%	3.67%	-4.29%	3.67%	-7.91%
PM (g/bhphr)	-54.64%	-51.17%	-73.47%	-86.73%	-87.54%	-74.89%	-67.15%	-89.33%	-79.06%	-86.98%	-51.17%	-89.33%

The graphical representation of the 8-mode composite results in Figure 23 shows that the devices without a DOC had filtration efficiencies less than 75% and were generally lower than devices with a DOC. Device 4 with a DOC showed filtration efficiency that was less than that of devices 3 and 4 without a DOC. In all other instances the addition of a DOC increased the PM filtration efficiency.

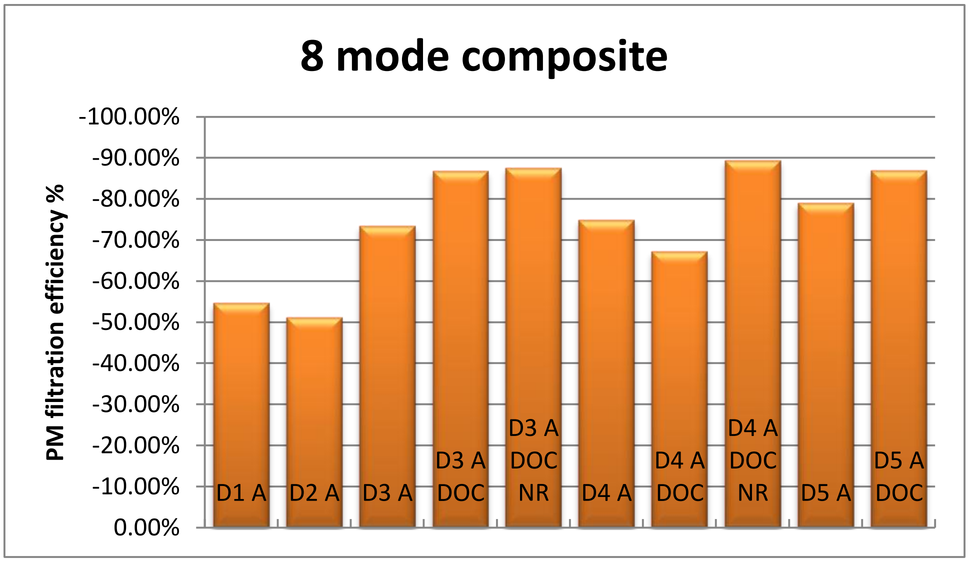

Figure 23: 8-mode Composite PM, Active Only

The 4-mode composite analysis also showed that device 4 with a DOC and new regeneration strategy had the greatest PM filtration efficiency. The results vary slightly from the results of the 8-mode composite analysis due to the different weighting factors used in the two composite analyses. In some cases, as in device 3 active, there was a decrease in the PM reduction efficiency by 20%. This shows that in some cases a device may exhibit good filtration characteristics for the 8-mode composite, but not the 4-mode composite analysis. This operational difference from standard 8-mode reduction efficiency to that of the 4- and 8-mode composite analyses could be due to excess PM production at operational levels that the engine would not typically be operating under a “real world” scenario. CARB uses the 4-mode composite values for the final evaluation of a DPF and its certification for implementation. Table 22 shows the numerical results of the 4-mode composite analysis.

Table 22: 4-mode Composite Emissions Analysis, Active Only

4 mode composite												
	D1 A	D2 A	D3 A	D3 A DOC	D3 A DOC NR	D4 A	D4 A DOC	D4 A DOC NR	D5 A	D5 A DOC	min	max
HC (g/bhphr)	-9.62%	-11.87%	-8.17%	-76.03%	-79.57%	-13.31%	-67.37%	-82.89%	-11.50%	-79.28%	-8.17%	-82.89%
CO (g/bhphr)	-5.88%	13.67%	12.86%	-81.95%	-60.18%	6.22%	-47.09%	-35.45%	18.05%	-48.52%	18.05%	-81.95%
CO2 (g/bhphr)	0.13%	1.62%	-2.76%	-1.02%	-0.15%	-0.85%	-1.70%	0.03%	-0.58%	0.16%	1.62%	-2.76%
NOx (g/bhphr)	0.09%	1.09%	-2.76%	-0.80%	-0.78%	0.36%	-1.20%	-1.48%	-0.41%	-0.77%	1.09%	-2.76%
NO (g/bhphr)	1.97%	3.52%	-0.51%	-14.71%	-13.80%	3.55%	-1.06%	-12.45%	2.46%	-12.14%	3.55%	-14.71%
PM (g/bhphr)	-59.13%	-55.65%	-53.73%	-79.85%	-83.03%	-66.76%	-67.90%	-84.98%	-66.57%	-79.44%	-53.73%	-84.98%

The graphical representation of the data in Figure 24 shows both the increases and decreases exhibited by the 4-mode composite analysis when compared to Figure 23. Table 23 shows the calculated difference between the two as an absolute value. It is also important to note that differences between device 3 active with a DOC and device 4 active with a DOC and new regeneration became were reduced when the 4-mode composite analysis was done going from a difference of 22.18% in the 8-mode composite values to 17.08% difference in the 4-mode. From these findings it is clear that device 4 with a DOC and a new regeneration strategy was the most successful device in terms of PM reduction. It showed the largest reductions for both the 4- and 8-mode composite analyses. This device also reduced HC for both comparisons at -76.51% for the 8-mode composite and -82.89% for the 4-mode composite and had minimal effects on the changes of the other emissions constituents exhibiting a nominal increase from baseline of CO_2 at 0.03% and 1.59% from the 4 and 8-mode composite results, respectively.

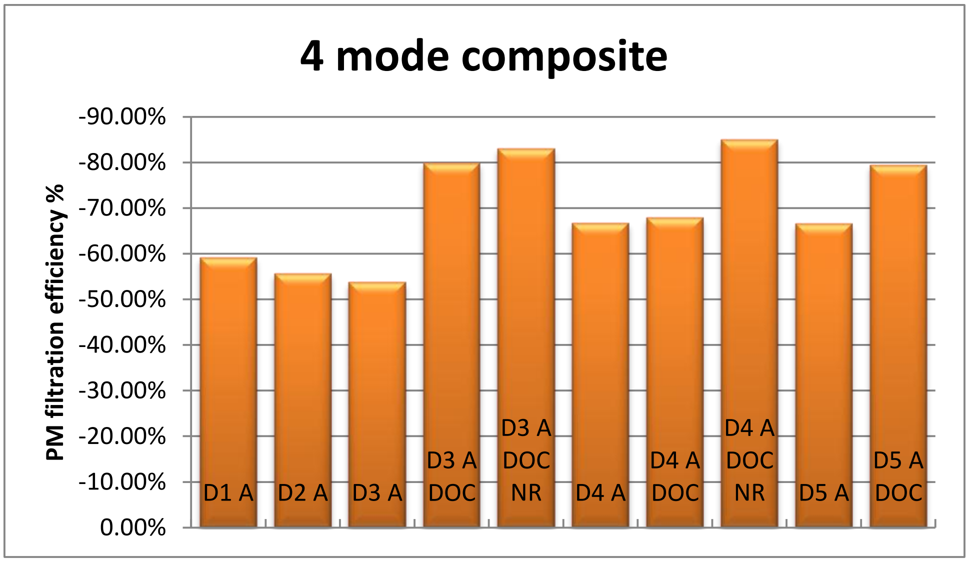

Figure 24: 4-mode Composite PM, Active Only

Table 23: 4-mode and 8-mode Composite Emissions Analysis Difference, Active Only

Composite Difference										
	D1 A	D2 A	D3 A	D3 A DOC	D3 A DOC NR	D4 A	D4 A DOC	D4 A DOC NR	D5 A	D5 A DOC
HC (g/bhphr)	1.41%	1.13%	0.07%	7.17%	7.61%	3.60%	6.27%	6.37%	1.65%	10.29%
CO (g/bhphr)	10.31%	12.92%	1.17%	6.99%	9.00%	9.77%	9.25%	27.74%	12.86%	16.14%
CO2 (g/bhphr)	0.36%	0.02%	0.63%	0.68%	1.52%	0.77%	2.02%	1.56%	0.31%	1.60%
NOx (g/bhphr)	0.04%	0.34%	0.81%	1.46%	0.99%	0.49%	1.31%	1.75%	1.50%	1.60%
NO (g/bhphr)	0.14%	0.04%	0.75%	6.79%	7.45%	0.09%	2.10%	8.32%	1.21%	7.85%
PM (g/bhphr)	4.49%	4.47%	19.73%	6.88%	4.52%	8.13%	0.75%	4.35%	12.49%	7.54%

5.2.2 Evaluation of Soxhlet Extraction

A Soxhlet extraction was performed on the test engines' PM filters to determine the effect that the SOF generation of the engine had on the PM results of an 8-mode analysis. SOFs are generally heavier particles with larger size as defined by Czerwinski et al. as solid kernels enveloped with SOF [5]. The traditional PM particles are defined by Kittleson as nanoparticles that range between 50 nm and 1000 nm [18]. The SOF analysis produced a working knowledge about the effect these heavier particles can have on the resulting filtration efficiencies that are determined gravimetrically. These results are shown below in Figure 26.

However, the Soxhlet extraction process can cause some of the T60A20 filter material to be removed during the extraction process. To analyze this effect a series of 11 field blanks were run through the extraction process. These field blanks were not introduced to any exhaust gas and were simply utilized for a basis of comparison.   An average mass extracted from the field blanks was 0.1132 mg. The results of the field blank extraction are shown graphically in Figure 25.

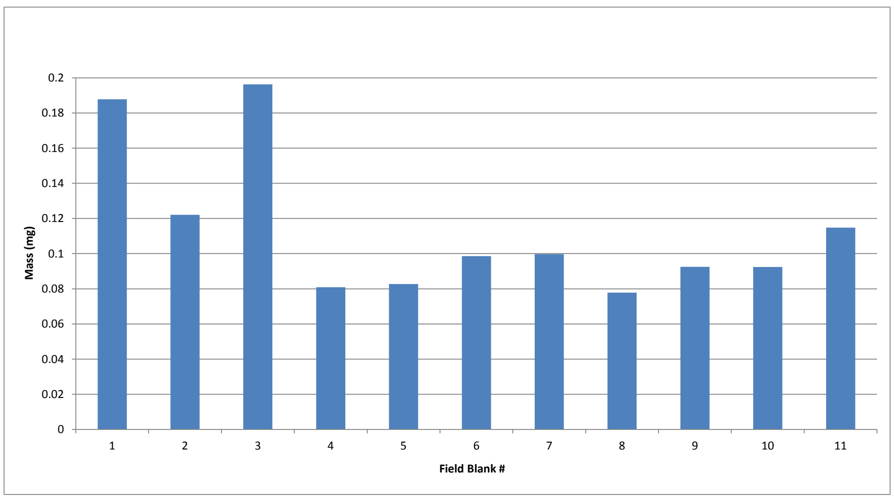

Figure 25: Field Blank Mass Extraction

The production of SOF is shown graphically in Figure 26. It is important to note that instances of SOF production above 100% are related to errors within the measurement and analysis of the SOF as explained above. These results, however, show trends in the production of SOFs with the most elevated levels being witnessed in modes 3, 4, 7, and 8. For all three baseline tests there is considerable elevation of SOFs at mode 8 which is the idle set point of the engine.

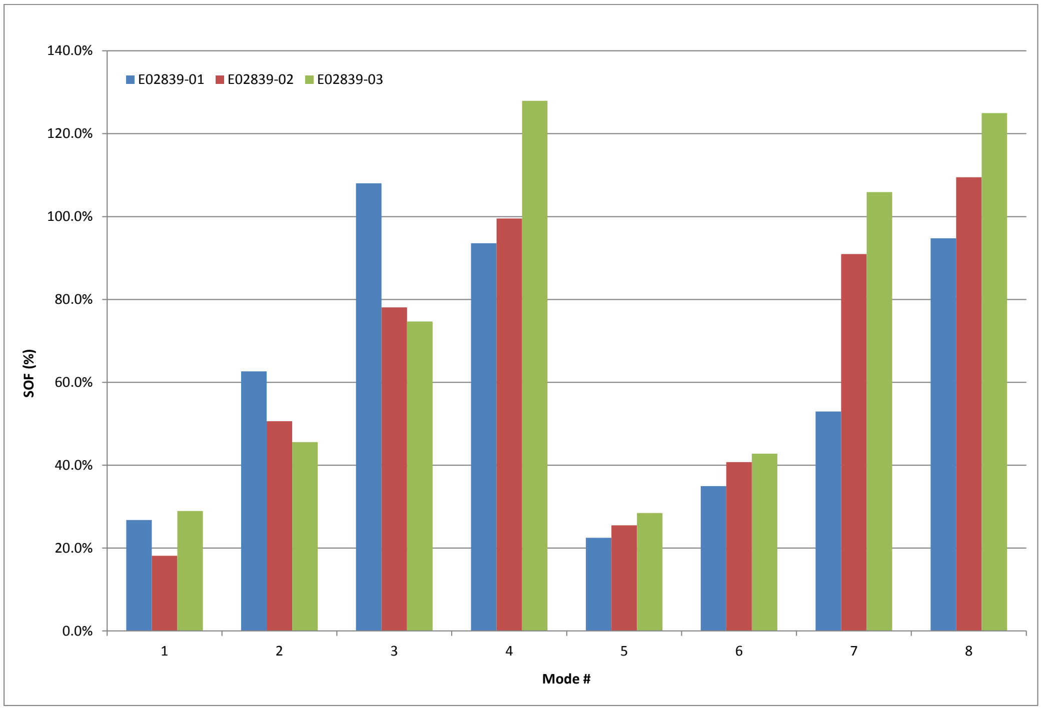

Figure 26: Soluble Organic Fraction Extracted Percentage

To further investigate the effects of SOF on the PM filtration efficiency results a greater accuracy within the testing regime is necessary. These results merely show trends in SOF production, but the actual results are convoluted by measuring inaccuracies. This procedure would be better investigated with an altered 8-mode test where longer measuring periods at each mode could be achieved. This extended time at each mode would increase the accuracy of the measurements since the variation in the amount of material removed from the filter would be smaller relative to the net mass of PM or the mass of organic material removed from the PM.

5.2.3 Evaluation of Backpressure Characteristics

The backpressure characteristics for each device are graphically represented in the figures below. Figure 27 represents the baseline evaluation of backpressure across the 8-mode cycle. This Kubota engine experiences a peak back pressure around 40 in H_2O when run without a DPF in “real world” implementation. The backpressure was set to simulate the backpressure experienced in “real world” scenarios by placing a throttling valve after the exhaust manifold. Each of the 8-modes is represented by an operational backpressure which can be clearly seen by the eight steps shown in Figure 27. Note that the steps, indicative of the different modes, are due to the data acquisition only collecting the data during a specific time period for each mode. Conclusions about the time it takes to regenerate should not be drawn for data between modes.

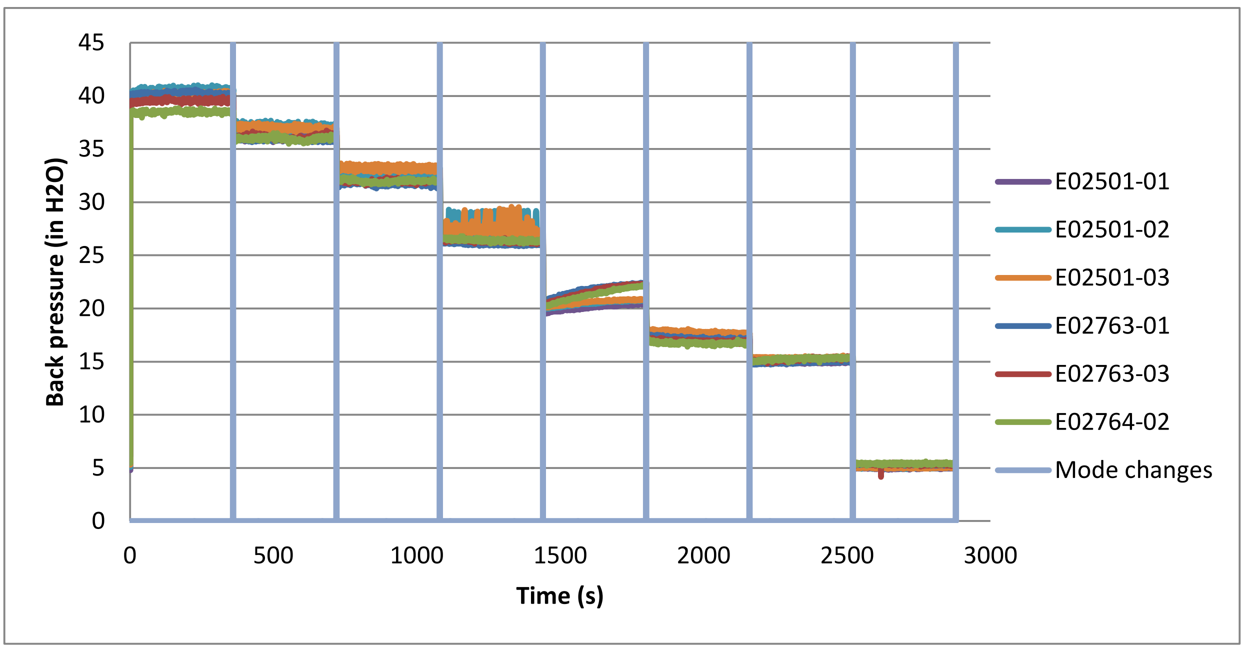

Figure 27: Baseline Backpressure Analysis

To demonstrate the variability in backpressure that can occur for a given device with multiple tests performed, device 2 active was selected. The graph below shows the three tests performed on this device and the variability associated with the back pressure from test to test. This variation can be attributed to the loading characteristics (history affects) of PM and the internal actuation of the DPF. A relatively large change in pressure, from high to low, is indicative of regeneration or a mode change. Figure 28 shows that while run E02503-03 has six major steps in back pressure run E02503-02 only has five while run E02503-01 only has four. The regeneration strategy was consistent for all three iterations. This shows that although the device is operating in the same manner, such variables as residual PM from previous runs could influence the regenerations that occur even whilst in a fixed laboratory setting. Thus this behavior may have the potential to influence the regeneration efficiency.

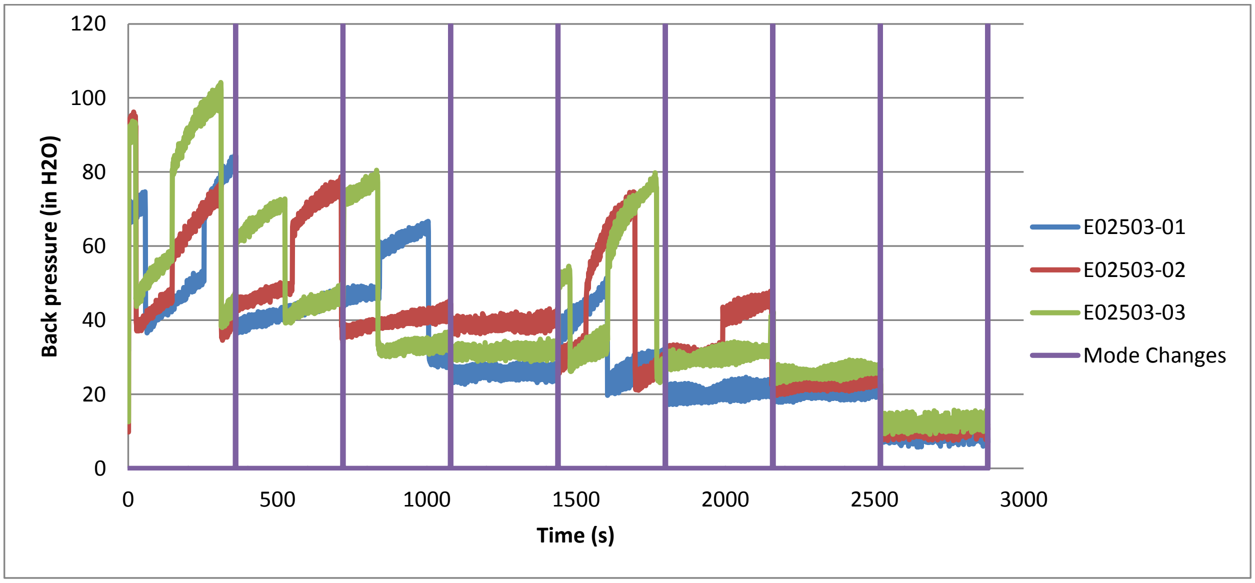

Figure 28: Continuous Backpressure Traces for Device 2 Active

Device 3 was chosen to show the effects of the addition of a DOC as well as the passive operation. Figure 29 once again shows the variability in backpressure for the same device with multiple runs. It is important to note that in run E02765-02 a peak back pressure nearly 180 inches of H_2O occurred in the first 500 seconds where as in run E02765-01 the pressure was almost 60 inches of H_2O lower. Three regeneration events occurred for both runs over the course of the test. This analysis also showed that E02765-02 had higher back pressure than that of E02765-01 until near the two thousand second mark, at which point E02765-01 had a lower back pressure. This can be attributed to a regeneration event that oxidized more PM than the other device resulting in less restriction at this point which correlates to a decrease in back pressure.

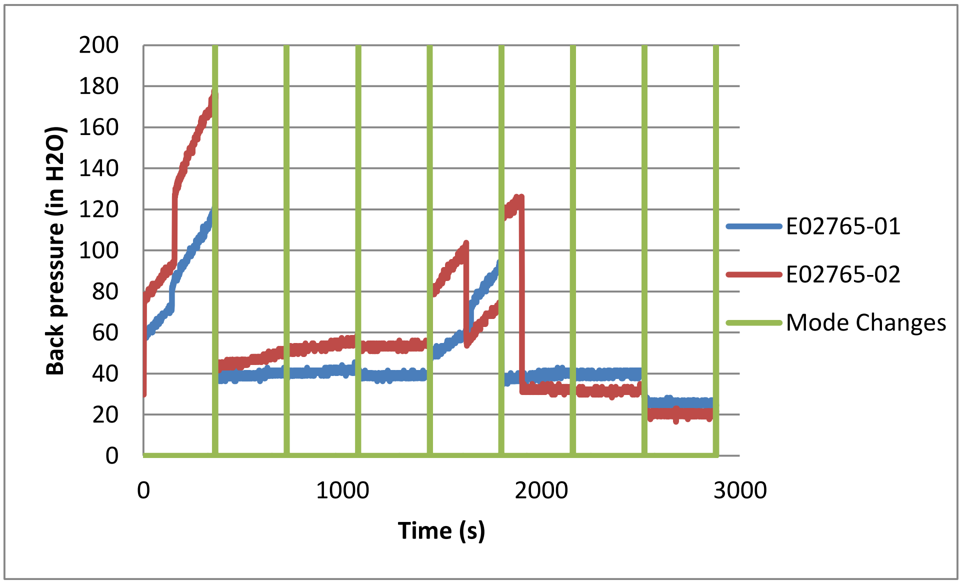

Figure 29: Device 3 Active Backpressure Analysis

The effects of implementation of a DOC on the back pressure characteristics of a device are shown below in Figure 30. A DOC seems to have nearly no effect on the back pressure. Although slight increases can be noted, these increases could be attributed to the additional piping associated with the DOC and variations normally seen from test to test.

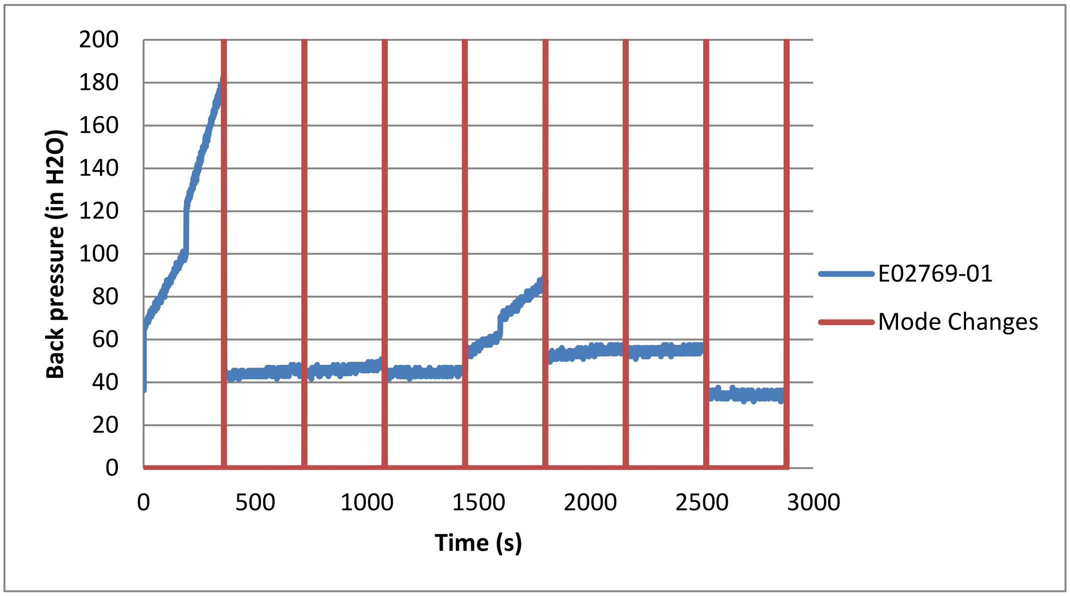

Figure 30: Device 3 Active with DOC Backpressure Analysis

The effects of passive operation of this device are shown below in Figure 31. The back pressure builds steadily and is much higher than that of the active DPFs. Just past the 2000 s mark there is a sharp decrease in the back pressure, which can be attributed to a passive regeneration. Once the regeneration occurs the back pressure decreases substantially.

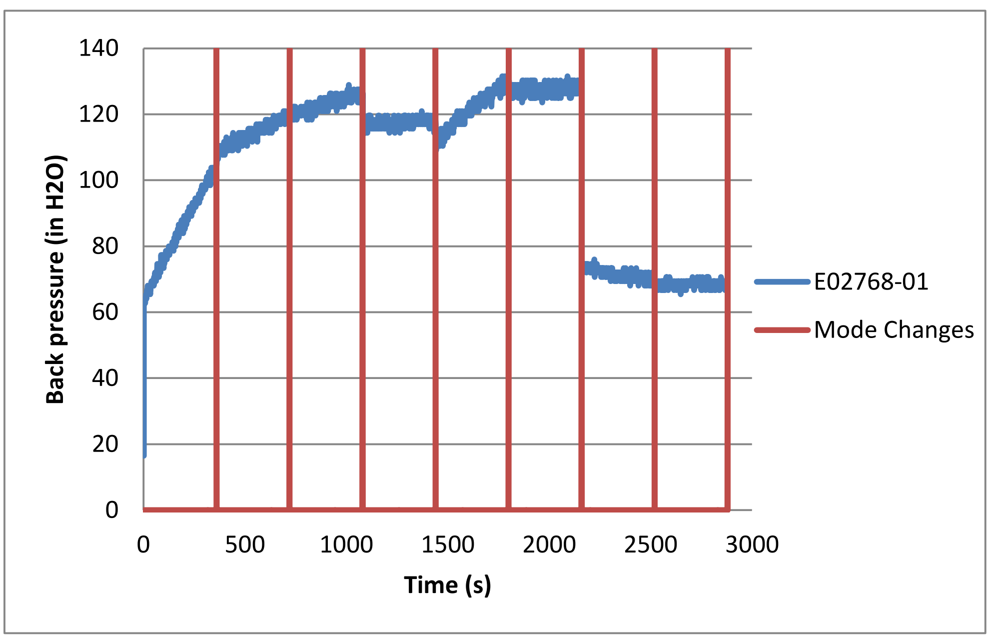

Figure 31: Device 3 Passive Backpressure Analysis

The effect of a DOC on the passive operation of the device shows that an increase in the back pressure may occur as shown in Figure 32. As is expected the addition of a DPF increased the back pressure on the engine. In instances where the device was operated passively the pressure remained higher than that of the device when operated actively which is as expected since active operation is meant to operate at a consistent backpressure that is lower than a passive DPFs back pressure. The same device run multiple times proved to generate different backpressure characteristics from run to run. The trends shown above in Figures 27 through 32 are supplemented by additional figures in the appendix.

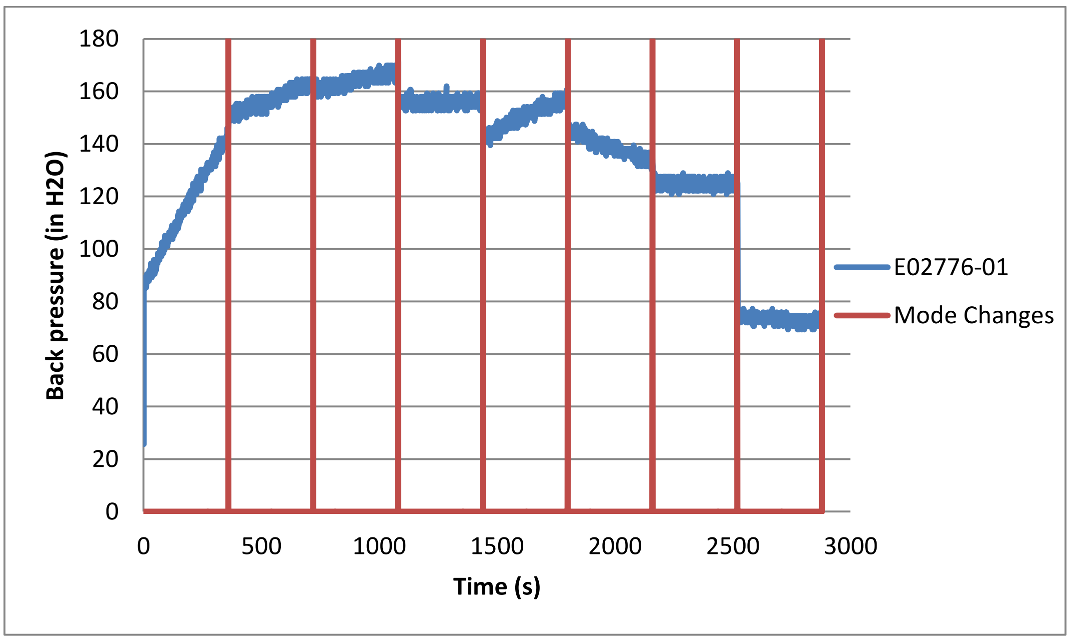

Figure 32: Device 3 Passive with a DOC

To further demonstrate the effects of backpressure on regeneration a table showing the CO_2 results as well as the average modal backpressure in conjunction with PM filtration efficiency was made. In Table 24 the CO_2 increases can be correlated to direct increases in fuel consumption where a 1% increase in CO_2 would be quantified as a 1% increase in fuel consumption. The largest PM reduction across the modes of operation is shown to be -98% which is coupled with an increase of fuel consumption of 5%. It is clear the engine operation point also has an effect on the correlation between backpressure and fuel consumption. This is shown by mode 1 with a -96% reduction of PM from the baseline, which is also coupled with a mere 3% increase in fuel consumption, which is the lowest increase in fuel usage for all modes.

Table 24: Backpressure Analysis with Brake Specific PM and CO_2

Device 3 Passive with a DOC							
Mode	1	2	3	4	5	6	7
Average Backpressure (in H2O)	115.5	157.0	164.1	155.9	150.5	138.9	124.5
PM brake specific % reduction from baseline	-96%	-94%	-95%	-93%	-98%	-93%	-90%
Carbon dioxide brake specific % increase from baseline	3%	4%	6%	11%	5%	4%	5%

Chapter 6 Conclusions and Recommendations

6.1 Conclusions

It is important to note that both device 1 and 2 were intended to achieve a PM filtration efficiency of 80%. Devices 3 through 5 were meant to have an even higher filtration efficiency of 95%. Neither of these goals were met, hence multiple iterations of each device were investigated. The conclusion of these findings is that the best performance for both 4- and 8-mode composite results was device 4 active with a DOC operating with an improved regeneration strategy This device reduced HC by -82.89%, CO by -35.45%, NOx by -1.48%, NO by -12.45% and PM by -84.98% from baseline for 4-mode composite analysis. The addition of a DOC on device 3 helped the reduction from baseline of the iteration of device 3 with a DOC and new regeneration strategy to values close to that of device 4 active with a DOC and new regeneration strategy. The 4-mode composite values for this device are HC reduction from baseline of -79.57%, CO reduction of -60.18%, CO_2 of -0.15%, NOx of -0.78%, NO of -13.80% and PM at-83.03% The increase from baseline of the gaseous components of the emissions was not deemed significant with increases below 4% while reductions in constituents such as HC were observed with all devices equipped with a DOC all while achieving over 65% reduction. The Soxhlet extraction performed on the gravimetric filters loaded with PM produced by the engine proved to show trends in the production of SOFs, however the clarity in the gravimetric data was still elusive with the available mass on the PM filters. Although SOF production did occur it was unclear what specific effects it had on the gravimetric PM analysis on the devices tested. The passive operations of these devices showed the potential filtrations that can be achieved from the devices, but these large reductions are also coupled with large increases in back pressure which drive up the fuel consumption of the engine by up to 11% at certain modes. Although neither of the devices met the goal for which they were designed valuable data were available that helped understand the required development of the next generation of devices.

6.2 Recommendations

The recommendations for alterations to the devices are first the implementation of a DOC. The largest reductions were found using this supplemental device. Secondly, maintaining a maximum acceptable operating back pressure with allotment for a safety factor should be considered. The filtration efficiency is greatly increased with the more PM loading. Higher PM filtration efficiencies could be produced with slight hindrance to the operation of the engine. It is suggested that partial regenerations of the chambers by start of burn and then immediate chamber actuation so as to maintain a larger PM layer and creating shorter duration regenerations with increased frequency. To further develop the testing of these devices the implementation of a set preloading of each device prior to an 8-mode test could also be beneficial; this is because the actuation of the DPF would be clearer. The DPFs would all start at the same state before testing occurred and should in theory produce the same trends for regeneration when analyzed. To determine the effect of SOFs on the gravimetric results for the PM filtration efficiency the 8-mode test should be extended at each mode in duration. This would result in larger quantities of deposited PM and would improve the SOF analysis. Outfitting the DPFs with internal thermocouples to better understand the internal temperatures associated with the regenerations as well as normal operation would also shed more light on the operation of the device. Also supplementing the data with an active recording of the start and end of regeneration signals from the after treatment control system would be beneficial.

Chapter 7 References

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Appendix

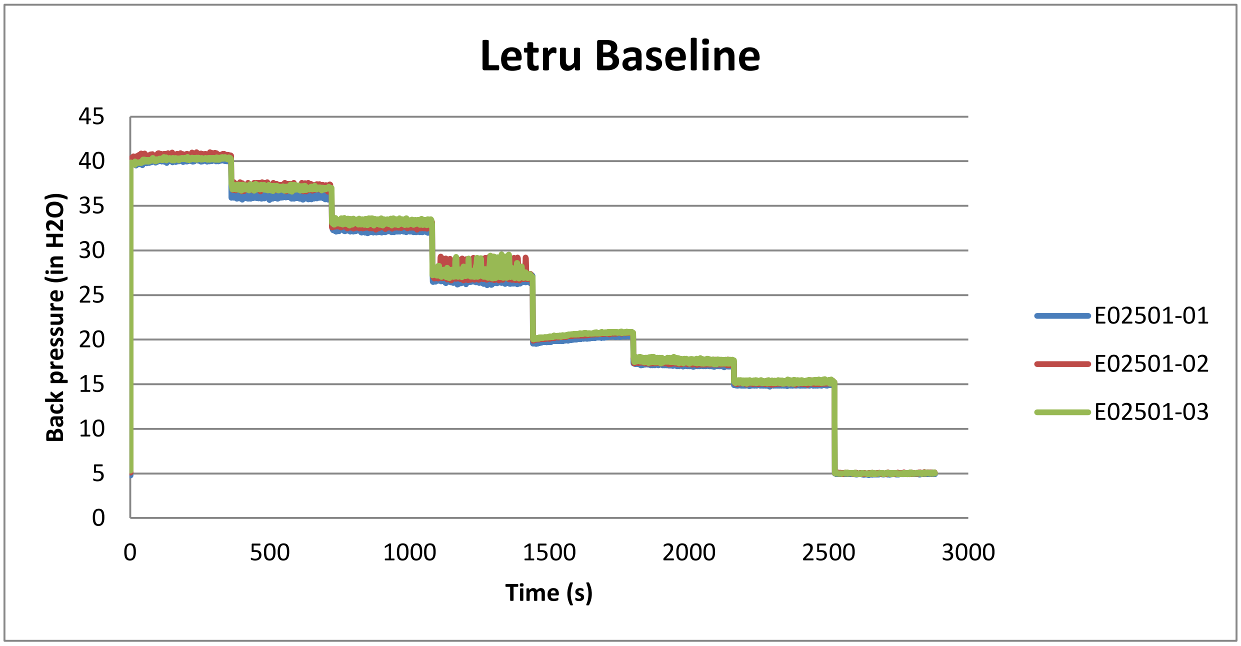

Figure 33: LETRU Baseline Backpressure Data

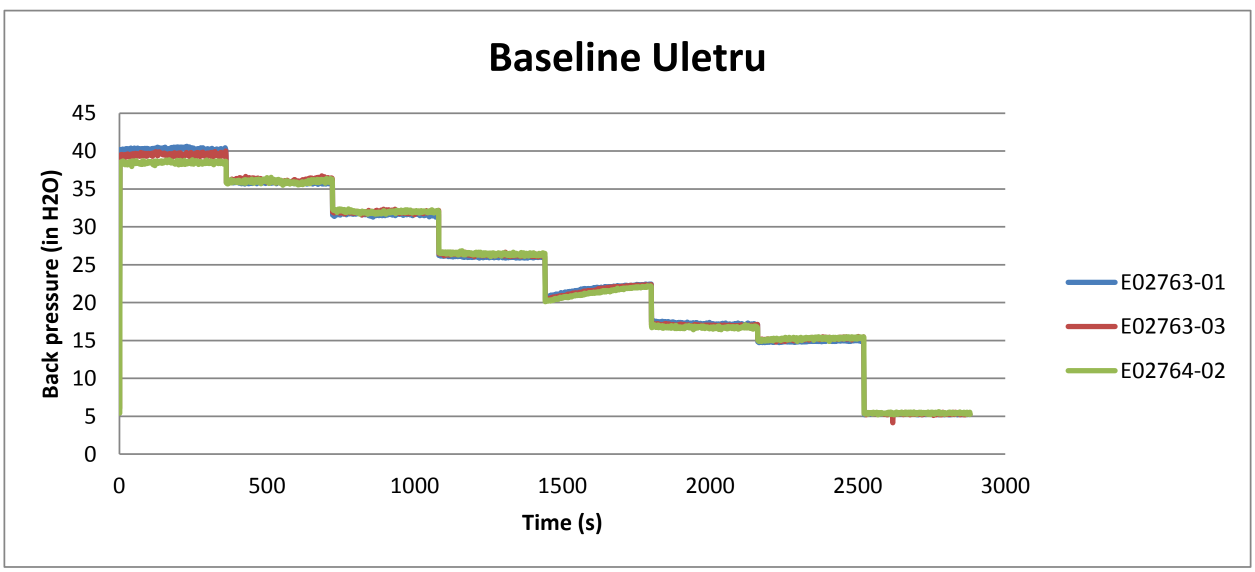

Figure 34: ULETRU Baseline Backpressure data

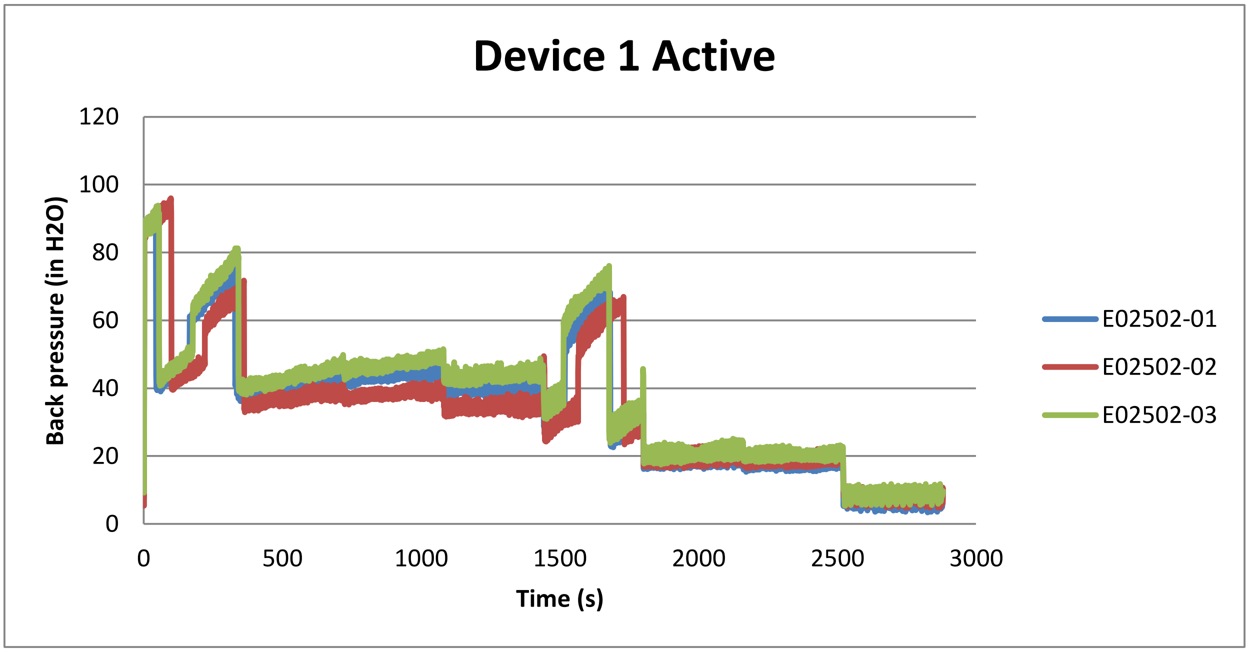

Figure 35: Device 1 Active Backpressure Data

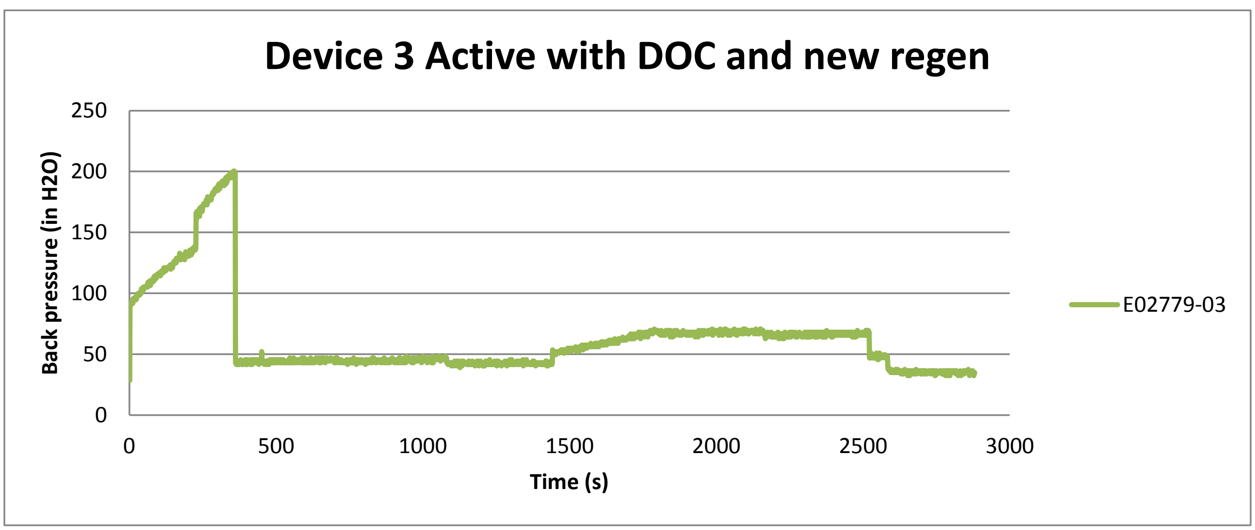

Figure 36: Device 3 Active with DOC and New Regeneration Strategy Backpressure Data

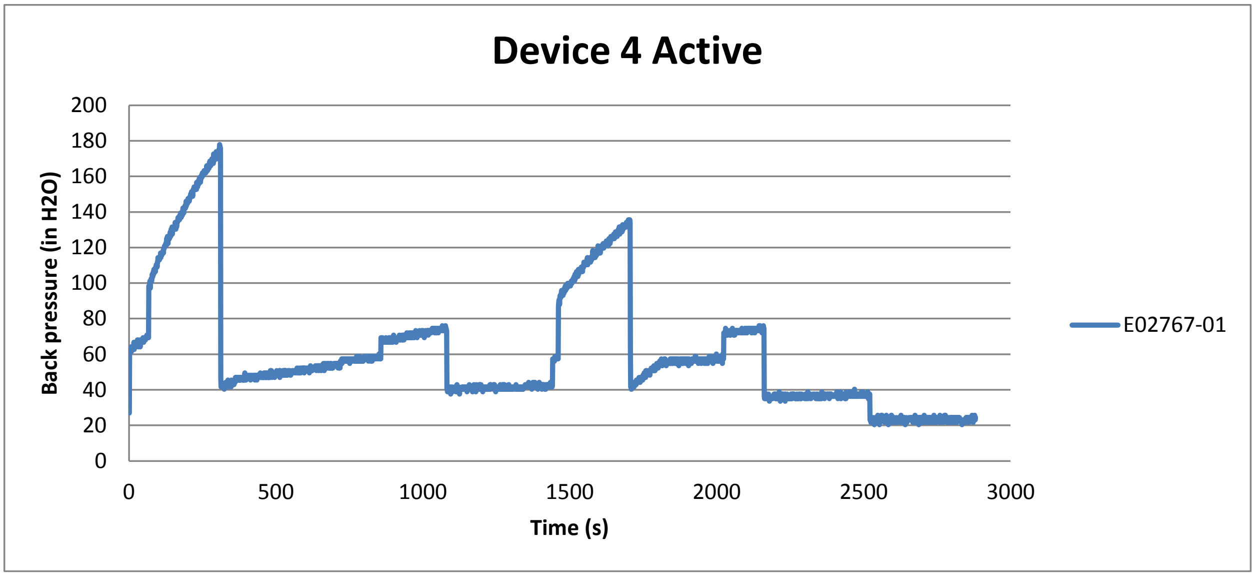

Figure 37: Device 4 Active Backpressure Data

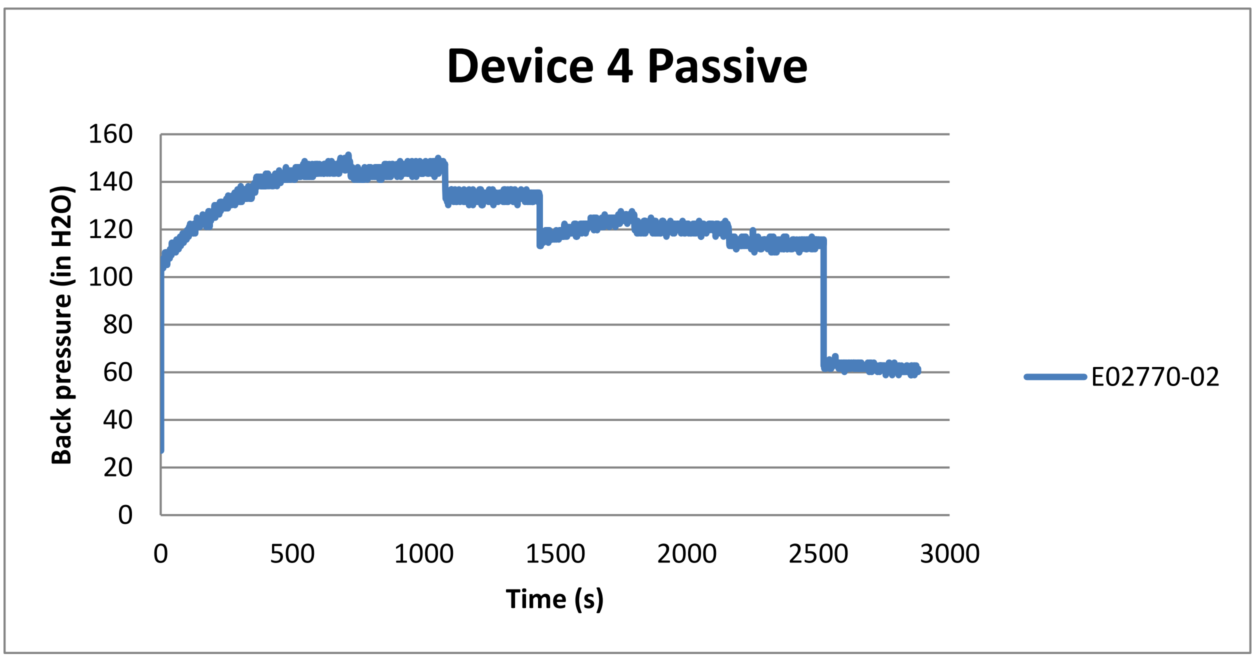

Figure 38: Device 4 Passive Backpressure Data

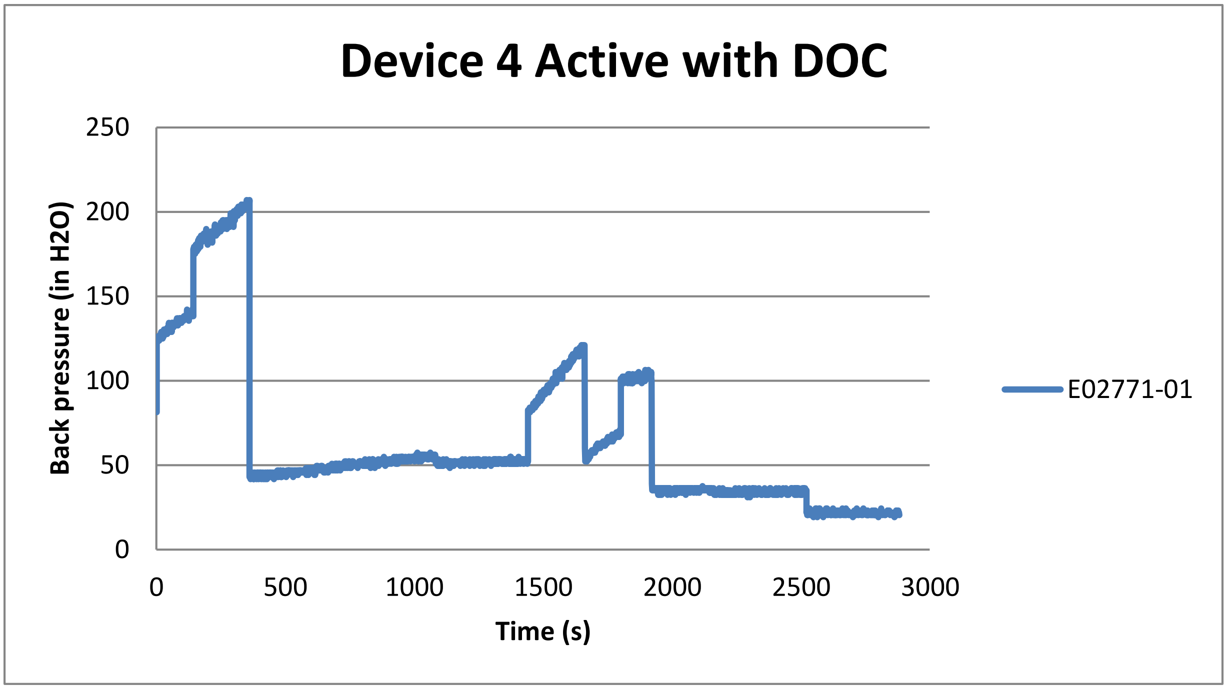

Figure 39: Device 4 Active with Doc Backpressure Data

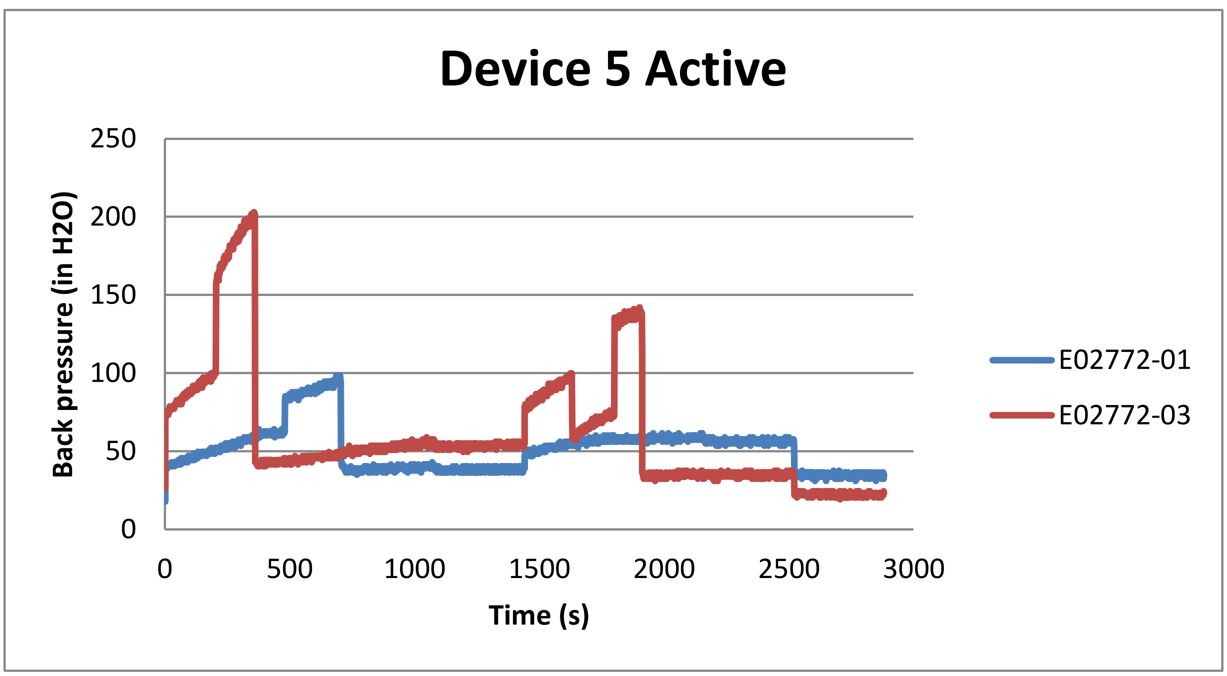

Figure 40: Device 5 Active Backpressure Data

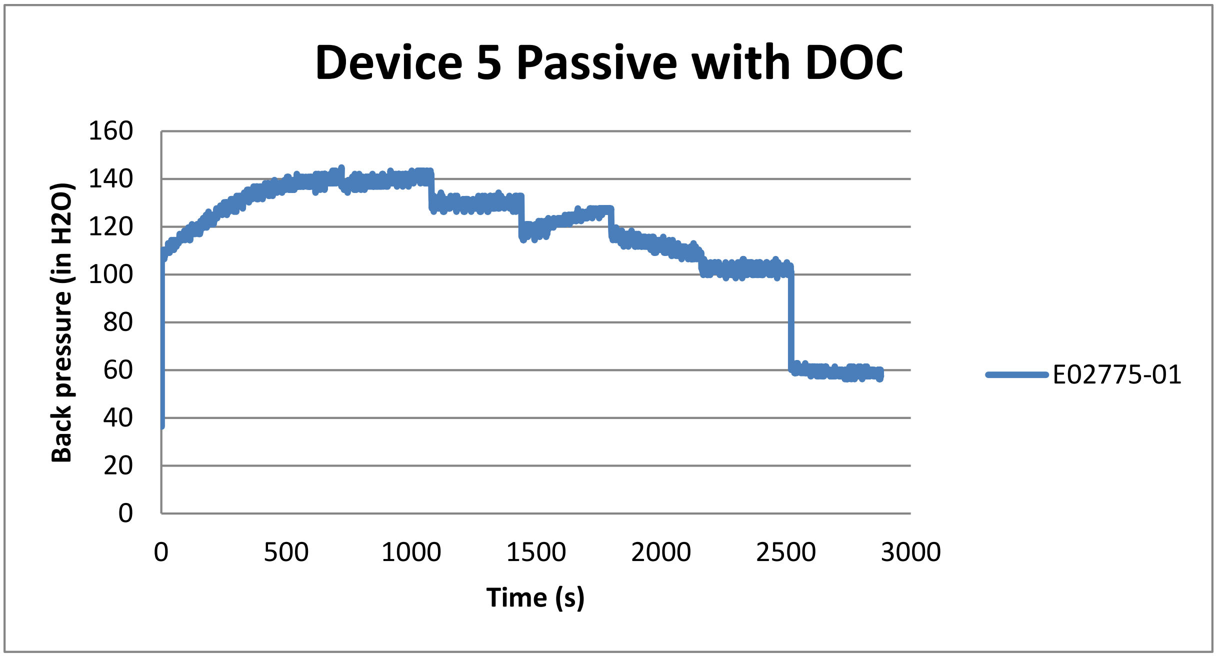

Figure 41: Device 5 Passive with a DOC Backpressure Data

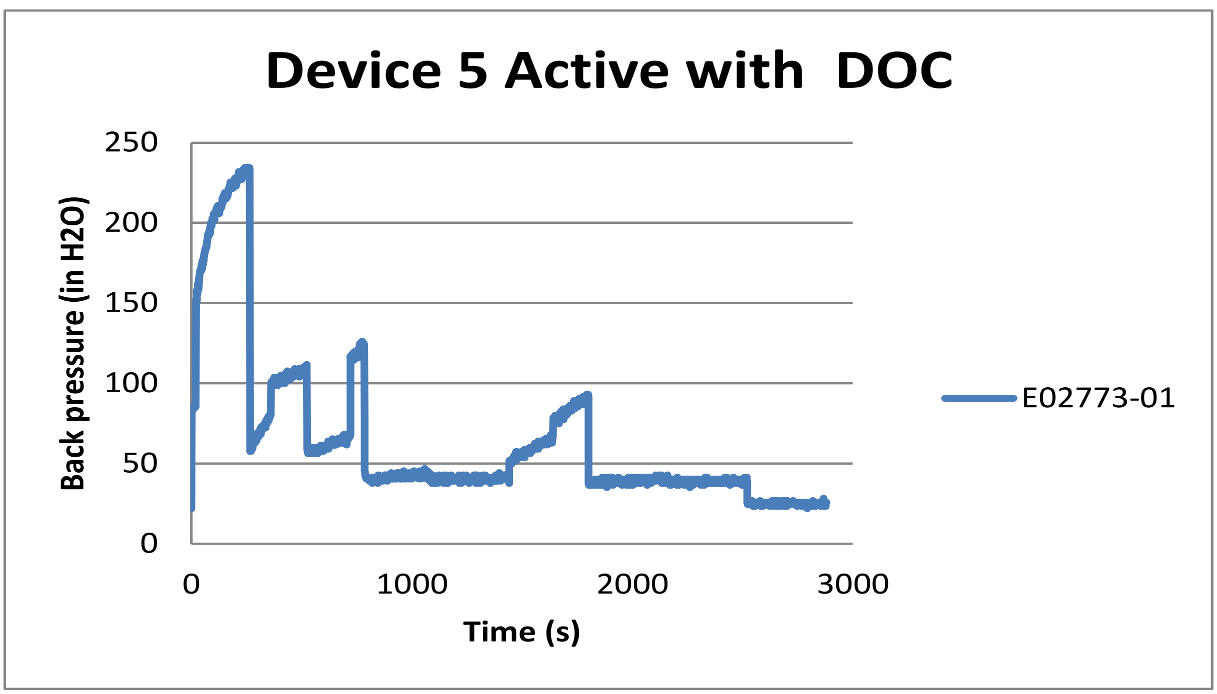

Figure 42: Device 5 Active with a DOC Backpressure Data